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**APOLLO LOGISTICS SUPPORT SYSTEMS
MOLAB STUDIES**

REPORT ON

**MOBILITY DEVELOPMENT TEST REQUIREMENTS
MOLAB LOCOMOTION SYSTEM**

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Prepared under Contract No. NAS 8-11096 by
Robert L. King, M. A. Sloan, W. B. Sponsler

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ABSTRACT

Presented in this report are the results of a study conducted for the purpose of establishing a framework of mobility development tests required for the MOLAB Locomotion System. Primary emphasis of the study is on four-wheeled vehicle configurations.

The rotating cone (when used in conjunction with the driven vehicle as described in the analysis) provides excellent lunar gravity simulation and offers considerable promise for use in determining the vehicles dynamic response to surface irregularities. The fixed cone (rotating vehicle) installation has an objectional feature, in that centrifugal forces affect the gravity simulation force.

A limited analysis of facilities required for the development test program is presented and pertinent recommendations are given; however, no attempt is made to design test articles, facilities, or special equipment.

APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

TASK ORDER N-24 REPORT ON

STUDY OF
MOBILITY DEVELOPMENT TEST REQUIREMENTS
MOLAB LOCOMOTION SYSTEM

Prepared under Contract No. NAS 8-11096 by
Robert L. King, M. A. Sloan, W. B. Sponsler

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For

SYSTEMS CONCEPTS PLANNING OFFICE
AERO-ASTRODYNAMICS LABORATORY

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SYMBOLS

v	=	Velocity (ft. /sec.)
L	=	Length (in.)
S	=	Travel distance (ft.)
λ	=	Ratio of prototype to model dimension (Scale)
b	=	Smaller dimension (width) of loading area (in.)
z_o	=	Sinkage (in.)
r	=	Soil particle size (in.)
θ	=	Slope angle (deg.)
M	=	Mass (lb. sec. ² /ft.)
γ	=	Specific weight of soil (lb. /in. ³)
ρ	=	Mass density (lb. ft. ² sec. ²)
I	=	Moment of inertia (lb. ft. sec ²)
α	=	Acceleration (ft/sec. ²)
g	=	Acceleration of gravity (ft. /sec. ²)
ϕ	=	Angle of internal friction of soil (deg.)
k	=	Berstein's modulus of soil deformation (lb. /in. ⁿ⁺²)
k_c	=	Cohesive modulus of soil deformation (lb. /in. ⁿ⁺¹)
k_ϕ	=	Frictional modulus of soil deformation (lb. /in. ⁿ⁺²)
c	=	Cohesion of soil (psi)
n	=	Exponent of sinkage (dimensionless)
t	=	Time (sec.)
ω	=	Circular frequency (radians/sec.)
f	=	Frequency of vibration (cycles/sec.)
\bar{c}	=	Damping coefficient
\bar{k}	=	Spring constant of material (lb. /in.)
N	=	Wheel turning rate (rev. /sec.)
μ	=	Friction coefficient (dimensionless)
F	=	Force (lb.)
DP	=	Drawbar pull (lb.)
R	=	Motion resistance arising from soil compaction (lb.)
P	=	Ground contact pressure (psi)
HP	=	Horsepower (ft. lb. /sec.)
E	=	Bulk modulus of elasticity of soil (psi)

SUMMARY

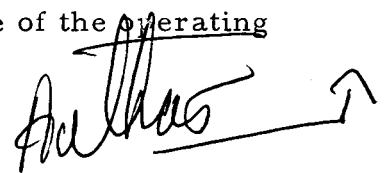
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This report presents the results of a study conducted by the Northrop Space Laboratories for the purpose of establishing a framework of mobility development tests required for the MOLAB Locomotion System. The study was performed for the Systems Concepts Planning Office of the Marshall Space Flight Center under the terms of contract NAS 8-11096.

Although four-wheeled, six-wheeled, and multi-wheeled train concepts are considered, the primary emphasis of the study is on four-wheeled vehicle configurations. The resulting development test approach encompasses early 1/6 th scale model tests to obtain trend information, tests of full-scale components, comparative testing of competitive systems using a flexible test bed concept and, ultimately, prototype tests of the selected system under simulated lunar gravity conditions.

A limited analysis of facilities required for the development test program is presented and pertinent recommendations are given; however, no attempt is made to design test articles, facilities or special equipment.

An analysis is also made of scale-model testing and conversion ratios (scaling factors) are developed for converting experimental inputs and results of scale model tests conducted in the earth environment to lunar equivalent properties and performance of the operating prototype.

Authas 

SECTION 1.0

INTRODUCTION

The Apollo Logistics Support System (ALSS), now being considered for approval as a project under the NASA Manned Lunar Exploration Program, has as its broad objective the scientific exploration of the Moon. Various payloads, capable of delivery by the Saturn V launch vehicle, have been studied by the Marshall Space Flight Center (MSFC) to determine their potential with regard to the realization of this objective. A manned lunar surface vehicle called the MOLAB (Mobile Laboratory) shows considerable promise in this respect and is currently under intensive investigation by MSFC. In support of this work, the Northrop Space Laboratories (NSL) has performed numerous engineering studies under the direction of MSFC in accordance with the provisions of Contract NAS8-11096. This report summarizes the results of one of these studies performed by NSL as a Task Order titled "Study of MOLAB Mobility Development Test Requirements".

SECTION 2.0

OBJECTIVES

The mission objective of the MOLAB Locomotion System is to provide safe, reliable transportation to a two-man exploratory crew engaged in hazardous scientific investigations on the lunar surface for periods of up to 14 days. Accordingly, the objective of the study reported herein was to outline the tests required to develop a system capable of providing the MOLAB with the mobility features required for this mission.

SECTION 3.0

GUIDELINES AND ASSUMPTIONS

The guidelines and assumptions for this study were, as follows:

- o Annex A - Engineering Lunar Model Surface (ELMS) and Annex G - Mobility Criteria, to the statement of work on the "Preliminary Design Study of ALSS Payloads" apply to this study.
- o Four-wheeled, six-wheeled and multi-wheeled train concepts will be studied with emphasis on four-wheeled configurations.
- o The test requirements shall be so devised as to permit the inclusion of tests intended to evaluate the relative merits of competing designs.
- o Scale factors (conversion ratios) are to be identified for both test articles and test equipment.
- o The scope of the study is not to include the design of test articles or equipment.

SECTION 4.0

MOBILITY DEFINITIONS

Mobility, as applied to the MOLAB, is interpreted as encompassing those capabilities of the Locomotion System which permit its use as a means of transporting men and equipment on the lunar surface. In this sense, the Locomotion System must act as a mobile platform which is capable of safely negotiating postulated slopes, obstacles and soils of varying physical properties while in the lunar environment without undue discomfort to the crew or damage to sensitive equipment and/or instrumentation. Thus, total performance, including maneuverability and dynamic response, are implicit considerations for the MOLAB transport mode. To provide a common framework of reference and to assure an understanding of the various mobility terms used throughout the text, the following mobility definitions have been adopted for the purpose of this report:

4.1 GENERAL

Mobility is defined as encompassing all performance aspects including maneuverability and ride characteristics of the MOLAB Locomotion System. These performance aspects establish the MOLAB's capability of operating in the transport mode in the lunar environment. Mobility may be further defined as being of a steady state or dynamic nature where each of these terms is defined, as follows:

o Steady State Mobility

Those mobility characteristics which predominate when the MOLAB is acted upon by forces which form a balanced or equilibrium condition. These forces cause the MOLAB to remain at rest or to move at a uniform speed, or to turn at a constant radius. In this report, steady state also encompasses those conditions that might better be termed "quasi-steady state". These include momentary transient conditions during a basically steady state operation at very low speeds. For example, as entering or leaving a turn or going from a level surface to a slope at very low speeds.

o Dynamic Mobility

Those mobility characteristics which predominate when the MOLAB is acted upon by unbalanced forces. These unbalanced forces cause the MOLAB to accelerate, decelerate, tip, slide, change direction or turning rate, or change attitude, as in going over obstacles. The overall dynamic response of the vehicle to surface irregularities, and the resultant structural loads and effects upon personnel and equipment

is termed ride characteristics.

o Performance Characteristics

In this report, performance characteristics are defined as mobility indices which establish the system performance limits, and form the basis for comparing the performance of one locomotion system (and to a certain extent the total MOLAB) with another. The performance characteristics are inherent in any given locomotion system by virtue of its (and the vehicle's) design.

4.2 MOBILITY PARAMETERS

For the purpose of this report, mobility parameters are defined as those factors or quantities which form the design considerations for the locomotion system and the MOLAB, and thus determine the basic design approach. Parameters are of two types, as follows:

o Variable Parameters

Variable parameters are those that can be varied to alter the performance characteristics of the MOLAB and are thus within the control of the designer. Examples are type and number of wheels, unitized or articulated chassis, and type and capacity of power system.

o Fixed Parameters

Fixed parameters are those which are essentially non-variable and are, in general, not within the control of the designer, i.e., they must be designed to, or around. Examples are the lunar environment (temperature, vacuum radiation, etc.), the physical characteristics of the lunar surface, and (by definition) the maximum mass and restraints of the delivery system.

SECTION 5.0

MOBILITY CHARACTERISTICS

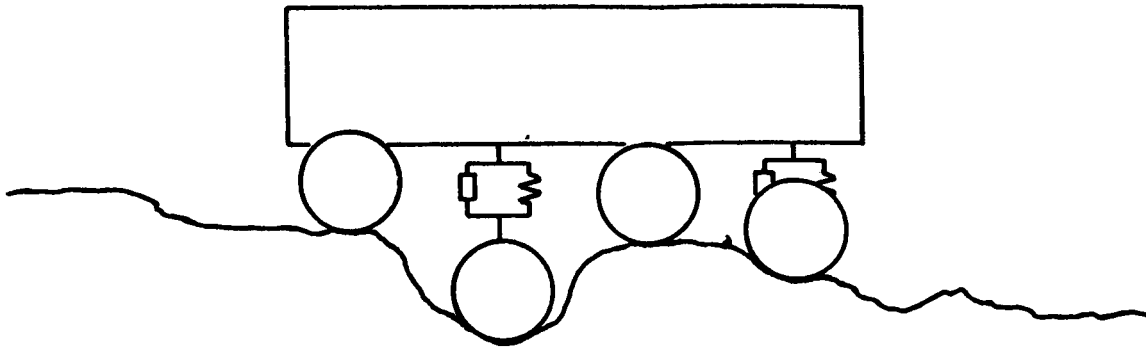
Mobility characteristics, when determined analytically and/or by test, serve as indices of the dynamic and steady state performance of the MOLAB when operating on the lunar surface. As indices, they can be used to gage the relative capability of (1) wheel concepts (4, 6 and multi-wheeled train concepts), (2) suspension designs (spring and damper concepts), (3) driving and steering units, and (4) overall vehicle concepts, including segmented chassis with articulated or flexible couplings--as appropriate. It should be noted that although the designer may change, or regulate (at his option) the variable parameters, he must do so within the constraints of the fixed parameters. In the paragraphs which follow, two of the variable design parameters are singled out for discussion in this contest.

5.1 OVERALL SUBSYSTEM CONFIGURATION

The overall subsystem configuration has a decided effect on all of the performance characteristics of the MOLAB. The degree of influence is, of course, dependent upon specific design details. For example, a multi-wheeled (more than 4), unitized body design presents the advantages of good ride characteristics, high volume and weight efficiency, and good low speed depression negotiation capability, but has disadvantages in that steering is difficult and the suspension system is complex. In comparison, a segmented body design, employing either articulated or flexible coupling links, has equal wheel loading over uneven terrain (results from independent pitch and roll action of modules) and good low speed obstacle crossing capability. However, its ride is poor, its volume to weight ratio is low, the design is complex and heavy, and steering stability and power synchronization are difficult. Fixed design parameters, on the other hand, will act to constrain the final design. For the two examples considered, it is quite conceivable that gross design limits imposed by weight and volume restrictions would make the segmented body design impractical or impossible and might, indeed, enforce selection of a unitized design concept. Figure 1 is a pictorial presentation of the relative merits of the two configurations discussed above. The segmented vehicle configuration shown in the sketch employs a flexible or articulated coupling link.

5.2 WHEEL CONFIGURATION

The number and type of wheels affect most of the performance characteristics of the Locomotion Subsystem, e.g., total thrust,



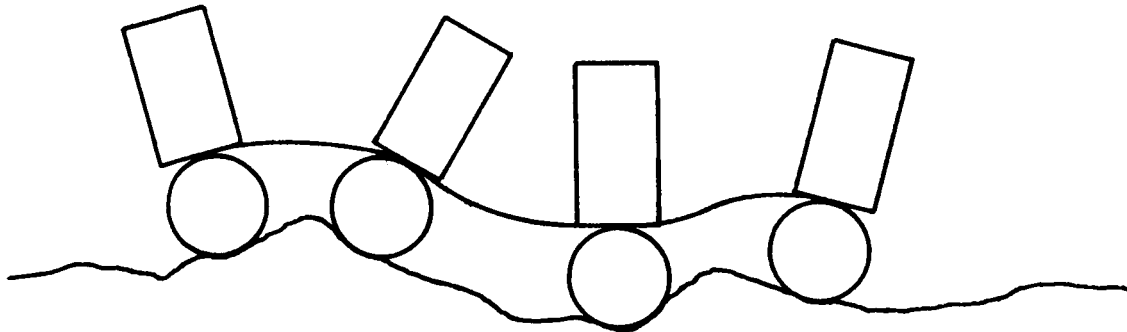
a. UNITIZED 8 WHEELED CONCEPT

Advantages

- o Good Ride
- o High Volume and Weight Efficiency
- o Good Depression Negotiation

Disadvantages

- o Difficult Steering (Conventional Types)
- o Complex Suspension



b. SEGMENTED (FLEXIBLE OR ARTICULATED) CONCEPT

Advantages

- o Good Obstacle Negotiation
- o Modular Body Segments
- o Body Steering Articulation
- o Equal Wheel Loading Over Uneven Terrain

Disadvantages

- o Poor Ride
- o Complex and Heavy Coupling Mechanisms
- o Poor Volume to Weight Ratio
- o Control Difficulty
- o Difficult Power Synchronization

FIGURE 1. UNITIZED AND SEGMENTED BODY CONCEPTS

internal and external wheel resistance, flotation limits, drawbar pull, slippage, ride, and the limiting velocities for stability. In consideration of all these factors, better overall performance might be predicted for the average lunar mission by employing a smooth semi-flexible wheel design. However, soil of a specific area selected for scientific exploration may be found to be predominately soft. If weight limitations constrain the vehicle design, it may be adviseable to add grousers to obtain what is tantamount to an effective increase in wheel diameter. Thus, the designer may choose to add grousers at the expense of operating at less wheel efficiency and reduced stability over limited hard surfaces in order to improve the more critical soft surface performance at minimum weight penalty.

SECTION 6.0

SCALE MODEL TESTING

Vehicles designed to provide surface transportation during lunar missions are small compared to conventional ships and aircraft. Consequently, cost considerations do not dictate as great a dependence upon the use of small scale models for their development as for the development of ships and aircraft. Nevertheless, scale models are an important research tool for use in the development of lunar surface vehicles. Their proper use, coupled with an analytical, computer based program, the full scale testing of components, and special full scale vehicle testing equipment and facilities will speed development of the prototype vehicle and reduce the costs of development programs. Specific applications of small model testing as related to a total development test approach for a Lunar Locomotion System are discussed in Paragraph 7.1; whereas, the basic theory applicable to model tests for such a system is presented in Appendix A. Since this latter aspect is very important if scale models are to be used in the development program, the findings of Appendix A are briefly summarized below.

6.1 CONVERSION RATIOS

A scale model must be so related to a physical system that observations taken on the model may be used to predict the performance of the physical system (prototype). Consequently, it is necessary that the physical relationships between the prototype hardware and its test model be established-if accurate prototype performance is to be predicted from the model test results.

Any analysis of the variables pertinent to scale model tests must be based on interrelationships which exist because of the dimensions of these variables. In Appendix A, such an analysis is accomplished. The results are summarized in Table 1. This table is also included in Appendix A as Table A-1. The table presents conversion ratios (model/prototype) for the variables shown. For scale model tests in the earth environment, experimental inputs and results must be divided by the ratio shown in the table for the corresponding variables to convert to lunar equivalent properties and expected prototype performance. For example, the drawbar pull (DP) required to overcome motion resistance during earth testing of a 1/6 th scale model must be divided by 1/36 (i.e., $DP = 36 DP_m$) to convert to the drawbar pull anticipated for the full-scale^p lunar prototype vehicle. Similarly, the compaction rolling resistance (R_c) for the lunar prototype is 36 times that determined for the 1/6th scale model, i.e., $R_c = 36 R_{c,m}$. The conversion ratios given in the table are based upon certain ground rules which were applied to the supporting analysis given in Appendix A. To prevent misinterpretations, qualifications which must be borne in

TABLE 1. MODEL/PROTOTYPE CONVERSION RATIOS

VARIABLES	CONVERSION RATIOS - MODEL/PROTOTYPE					
	(1) GENERAL RELATIONSHIPS	(2) $g_m/g_p = 1$ SCALE($\frac{1}{\lambda}$)	(3) $g_m/g_p = 6$ SCALE($\frac{1}{6}$)	(4) SCALE($\frac{1}{\lambda}$) SCALE($\frac{1}{6}$)	(5) SCALE($\frac{1}{6}$)	(6) $M_m = M_p/6$
Linear dimensions of mechanisms and surface features	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Mass density (ρ) of mechanisms and soil	$\lambda \left(\frac{g_p}{g_m} \right)$	λ	6	$\frac{\lambda}{6}$	1	$\frac{1}{6}$
Applied force (F), drawbar pull (DP), mechanisms and soil, etc.	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Mass of mechanisms and soil	$\frac{1}{\lambda^2} \left(\frac{g_p}{g_m} \right)$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{6\lambda^2}$	$\frac{1}{216}$	$\frac{1}{6}$
Inertia of mechanisms (I)	$\frac{1}{\lambda^4} \left(\frac{g_p}{g_m} \right)$	$\frac{1}{\lambda^4}$	$\frac{1}{1296}$	$\frac{1}{6\lambda^4}$	$\frac{1}{7776}$	$\frac{1}{6}$
Horsepower	$\frac{1}{\lambda^{5/2}} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\frac{1}{\lambda^{5/2}}$	$\frac{1}{88}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	2.45
Travel distances, displacements, strain, etc.	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Wheel turning rate (assuming no slippage)	$\lambda^{1/2} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\lambda^{1/2}$	2.45	$(6\lambda)^{1/2}$	6	2.45
Frequency (forced or resonant vibration, and angular velocity) - of mechanical nature	$\lambda^{1/2} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\lambda^{1/2}$	2.45	$(6\lambda)^{1/2}$	6	2.45
Damping coefficient (\bar{c}) of wheels, suspensions, etc. (viscous only - not applicable to non-linear case).	$\frac{1}{\lambda^{3/2}} \left(\frac{g_p}{g_m} \right)^{1/2}$	$\frac{1}{\lambda^{3/2}}$	14.68	$\left(\frac{1}{6\lambda^3} \right)^{1/2}$	$\frac{1}{36}$	$\frac{1}{2.45}$
Spring constant (\bar{k}) of wheels, suspensions, etc. (linear springs assumed).	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Friction coefficient (μ), angle of soil internal friction (ϕ), slopes and angles (θ).	1	1	1	1	1	1
Grain size of soil (r)	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Modulus of soil deformation (k), since $c = 0$ for lunar soils, $k = k_0$ in column (3).	λ^n	λ^n	6^n	λ^n	6^n	1
Compaction rolling resistance (R) in soft soil, weight, etc.	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Contact pressure (P)	1	1	1	1	1	1
Contact Area	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Cohesion of soil (c)	1	1	1	1	1	1
Material strength, Young's modulus, elastic limit	1	1	1	1	1	1
Time of travel, fatigue life, wear, etc.	$\frac{1}{\lambda^{1/2}} \left(\frac{g_p}{g_m} \right)^{1/2}$	$\frac{1}{\lambda^{1/2}}$	0.41	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{2.45}$
Velocity of travel	$\frac{1}{\lambda^{1/2}} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\frac{1}{\lambda^{1/2}}$	0.41	$\left(\frac{6}{\lambda} \right)^{1/2}$	1	2.45
Sinkage (z_0)	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1

*For lunar soils, (c) can be assumed as zero.

mind when using this table are discussed briefly below.

Velocity (v) was selected as the dependent variable in the analysis and mass density (ρ), length (L), and gravity (g) were treated as variables which would be present in any experiment. Since the acceleration of gravity will influence the response of the vehicle when disturbed by a vertical force, Froude's number must remain invariant between the model and the prototype, i. e.

$$\left(\frac{v^2}{gL} \right)_m = \left(\frac{v^2}{gL} \right)_p$$

Additionally, contact pressures (P) are assumed to be equal ($P_m/P_p = 1$).

6.2 SELECTION OF SCALE

For the purpose of this study, mobility has been classed as steady state or dynamic, Test models can also be so classified. A detailed analysis of the appropriate scale to be used for each category of lunar model is presented in Appendix A. For both types of tests, it was established that the use of a 1/6th scale model is advantageous, for the following briefly summarized reasons:

o Dynamic Models

For tests with such models it appears advantageous to use prototype materials to avoid the problem of (1) obtaining exotic materials with density and strength characteristics which would satisfy the rigorous demands of similarity principles, or (2) using distorted models with the attendant problems of determining the proper corrections to be applied to the test results.

o STEADY STATE MODELS

For these models, the use of a scale other than 1/6th introduces the problem of obtaining a model soil of a density different from that of the postulated lunar soil. This conclusion is tentative and should be further substantiated since larger models have the advantage of greater ease of construction and accuracy of instrumentation.

Although similitude laws call for scaling of the model soil, this condition is rationalized as unimportant so long as the largest grains are small compared to the smallest detail of interest on the model.¹

SECTION 7.0

DEVELOPMENT TEST APPROACH

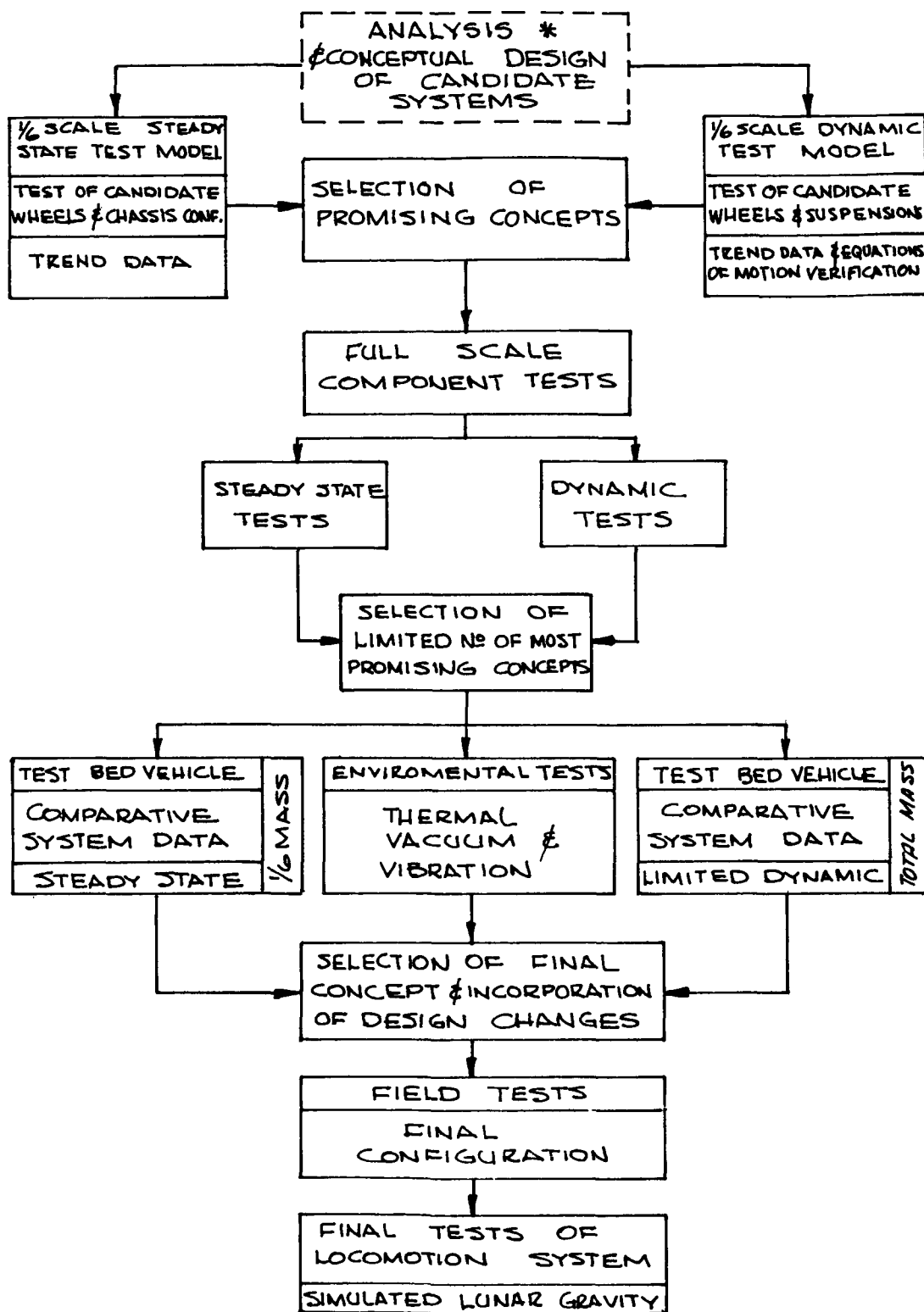
Outlined herein is a philosophy for the conduct of mobility development tests of lunar surface vehicles. Figure 2 is a diagrammatic representation of the test philosophy; whereas, Table 2 presents an outline of the resulting test approach. The reader will have need to refer to both at various points during the discussion which follows. Although the test approach presented implies a specific sequencing of activities, it should be noted that this sequencing is highly idealized and that certain test may overlap or, in some cases, a mix of tests may actually result. For instance, it is quite conceivable that the test program might be expedited if some of the early comparative testing for detailed wheel performance is obtained by employment of the Test Bed Concept (Tests 5 and 6 Table 2) which would permit testing of two or more wheels as an assembly.

7.1 SMALL MODEL TESTS

Where steady state performance is influenced primarily by the external configuration of the wheels and the surface over which they operate, small models may be used to advantage to investigate trends to obtain comparative data for candidate wheel and chassis concepts to assist in the formulation of basic hypotheses upon which reliable prototype analyses can be based and to check performance at various stages of design.

Small models may also be used for dynamic tests to obtain comparative data for various wheel and suspension concepts. In general, it is felt that this data should be used for such purposes as to establish comparative limits (velocities and obstacle sizes--worst case condition); and to determine the relative transmissibility of dynamic disturbances through the wheel and suspension system. Although scaling of wheel and suspension system flexibility and damping would be necessary, even for trend data, such scaling should be tailored to general concepts and not tied to specific detailed designs. Results should be considered as primarily qualitative and for the purpose of eliminating obvious misfits.

It should be noted that an analytical, computer based program, would lead the model testing discussed above and that results of the tests would be used to check the validity of the analytical predictions, including verification and/or modification of the dynamic equations of motion. Figure 2 shows the relationship of the analytical process to the scale model tests.



* NOTE: ANALYSIS AND CONCEPTUAL DESIGN IS NOT PROPERLY A PART OF THE TEST PROGRAM. IT IS INCLUDED HERE, HOWEVER, SINCE IT NECESSARILY LEADS TESTING. NOT INCLUDED IS THE CONTINUING PROCESS OF COMPUTERIZED MOBILITY ANALYSIS AND DESIGN WHICH HAS MANY ITERATIONS AT EACH OF THE TEST STAGES.

FIGURE 2. DEVELOPMENT OF LOCOMOTION SYSTEM
RECOMMENDED TESTS-FLOW DIAGRAM

TABLE 2
(Sheet 1 of 2)

DEVELOPMENT TEST APPROACH

DEVELOPMENT OF LOCOMOTION SYSTEM - REPRESENTATIVE TEST PROGRAM			
TEST OBJECTIVES	DESCRIPTION OF TEST ARTICLES	DEVELOPMENT PHASE	ENVIRONMENT
1. STEADY STATE - SMALL SCALE HARD SURFACE & COMPARATIVE SOFT SURFACE TESTS			
Obtain trend information for candidate wheel concepts and substantiate analyses for predicting prototype performance. Thrust, drawbar pull, slope performance and power requirements data. Obstacle performance runs should be at $v \approx 0$.	VEHICLE: ¹ 1/6 Scale Wheels: Various candidates Chassis: Ground clearance scaled Body: Mass distribution and cg only critical items	Concept Evaluation	Ambient except for humidity control to assure cohesionless soil. Hard and soft surfaces and slopes.
2. DYNAMIC REDUCED SCALE			
Determine response to surface irregularities at various velocities and establish comparative limits (velocities and obstacle sizes) for various candidate designs. Verify equations of motion. Primarily qualitative evaluation, but when coupled with results of Item 1, will result in elimination of some concepts.	VEHICLE: 1/6 Scale Wheels: Various candidates, accurately scaled deflection and flexibility. Chassis: Accurately scaled clearances. Suspensions: As appropriate but accurate scaling. Body: Inertias (all degrees of freedom), mass distribution, and cg critical. Note: Prototype materials required for wheels and suspension systems.	Concept Evaluation	Ambient. Hard surfaces with obstacles (worst case conditions)-slope variable.
3. STEADY STATE COMPONENT TESTS (SEE FIGURE 4)			
Obtain comparative performance data for candidate wheels and suspension systems remaining after tests under Items 1 and 2. Data obtained, as indicated, for each type of surface environment noted.	WHEELS AND SUSPENSIONS: Full size, various concepts. Test Articles are the same for a and b, below. a. Wheel internal losses (bearing and flexure) vs speed and vertical load. b. Thrust, drawbar pull, external resistance, slippage, and power vs vertical load; turning resistance vs load; flotation limits and sinkage vs load; etc.	Engineering Development	Ambient atmospheric plus surfaces noted below. Humidity control desirable. a. Hard surfaces b. Soft Surfaces
4. DYNAMIC COMPONENT TESTS (SEE FIGURE 5)			
Obtain comparative data on spring and damping characteristics of candidate wheel and suspension systems remaining after tests under Items 1 and 2.	WHEELS: Same as Item 3. SUSPENSION: Full Size, various concepts.	Engineering Development	Ambient atmospheric. Hard surface (variable slope) plus obstacles.
5. STEADY STATE SYSTEM PERFORMANCE² AND VERIFICATION OF EQUATIONS OF MOTION (SEE FIGURE 7)			
a. Obtain comparative data on candidate Locomotion Systems remaining after tests under Items 3 and 4. Investigate parameters listed in Item 3, plus limiting turn radius, and obstacle performance. Obstacle tests conducted at $V = 0$. b. Verify equations of motion (see discussion under Paragraph 7.3) and obtain parametric data for comparison of concepts.	TEST BED VEHICLE Full scale locomotion components i.e., wheels, axles, gears, suspension, steering and drive units, etc. Test bed and assembled locomotion components constructed to 1/6th MOLAB mass, or as nearly so as possible.	Engineering Development (narrowing of concepts)	a. Ambient atmospheric, plus hard and soft surfaces. Humidity control desirable. b. Ambient atmospheric. Hard surface with obstacles (worst case conditions). Slope changes included.

TABLE 2
(Sheet 2 of 2)
DEVELOPMENT TEST APPROACH

TEST OBJECTIVES	DESCRIPTION OF TEST ARTICLES	DEVELOPMENT PHASE	ENVIRONMENT
6. DYNAMIC SYSTEM PERFORMANCE (LIMITED DYNAMIC) - (SEE FIGURE 7)			
Obtain comparative data on candidate Locomotion Systems remaining after tests under Items 3 and 4. Data obtained as indicated for tests below. a. Performance and directional stability during braking (all modes)-sliding characteristics. b. Sliding stability during turns (level surface and slopes).	<u>TEST BED VEHICLE</u> Same as Item 5, except ballasted to same mass as MOLAB.	Engineering Development	Ambient atmospheric, plus conditions pertinent to each test, as below. a. Hard surface. $\mu = 1/6$ th lunar b. Same as a.
7. ENVIRONMENTAL TESTS OF CRITICAL COMPONENTS (SEE FIGURE 6)			
Obtain environmental exposure data, as required to demonstrate suitability of critical components or parts for use under anticipated operational conditions.	<u>CRITICAL COMPONENTS</u> FULL SCALE (wheels, bearings, axles, gears, seals, drive units, suspensions and steering units--for each concept still under consideration).	Engineering Development	Vacuum: 10^{-9} torr Temperature: 115 - 400°K Vibration: (as required)
8. FIELD TESTS OF FINAL CONFIGURATION			
Obtain field test data for qualitative evaluation of performance and handling characteristics	<u>VEHICLE</u> Complete Locomotion System; operable power system desirable; other systems not necessary.	System Development	Ambient atmospheric field test area(s); lava flow, volcanic ash, sand and gravel.
9. FINAL SYSTEM PERFORMANCE (SIMULATED LUNAR GRAVITY AND SURFACE)³ - (SEE FIGURE 8)			
Final mobility performance demonstrations for system concept selected as result of tests under Items 5 and 6. Includes both steady state and dynamic performance. Excludes thermal-vacuum tests of total system which can be included in tests of the integrated MOLAB system.	<u>LOCOMOTION SYSTEM</u> FULL SCALE (Equipped with MOLAB Mock-Up or ballasted to equivalent total mass of MOLAB)	System Development	Ambient atmospheric. Humidity control desirable for soft surface tests. Simulated lunar gravity and surface configurations, as shown in Note 3 below.

Notes:

1. The terms "Vehicle" or "Test Bed Vehicle" encompass (where appropriate) unitized or segmented bodies with articulated or flexible couplings.
2. By this time choice of system has probably been narrowed to 2 or 3 candidates.
3. Lunar gravity simulated by traveling (preferably maneuverable), support mechanism capable of supporting 5/6ths of the unsprung mass. Lunar surface simulated by test roadway incorporating features pertinent to specific test, e. g., hard or soft surfaces with or without obstacles, etc. If support mechanism is truly maneuverable along any vector in the horizontal plane and can maintain its constant lifting force, dynamic stability during turns on level surfaces can be determined. Driver could also be suspended for true physiological simulation.

7.2 FULL SCALE COMPONENT TESTS

In some cases, mobility test data (whether small scale or full size) can only be obtained with the complete Locomotion System. On the other hand, early data required to expedite final design decisions may be best obtained via the component test route. For instance, test data for obstacle performance can only be obtained by use of either the model or full scale system. On the other hand, data on internal wheel losses (bearing and flexure losses), with respect to speed and vertical load can only be obtained with the full size wheel which can readily be tested as an individual component under ambient atmospheric conditions early in the development program. Although small models may be used to advantage at an early stage of design to obtain wheel performance data (as noted above), detailed performance should be determined with the full size wheel. This is particularly true of flexible wheels where the cost of accurately scaled wheel flexibility and deflection characteristics is apt to approach that of the full-size wheel. Thus, the use of scale model wheels may not be economically justifiable, unless under the conditions stipulated in Paragraph 7.1. Also, the full-size wheel can be used to investigate all aspects of design--wear characteristics, fatigue life, and (most important in the final analysis) all aspects of performance from a vehicle mechanics point of view. Consequently, test equipment for obtaining detailed wheel performance should normally be designed for use with full-size wheels.

Full scale testing of the complete Locomotion System under the extremes of lunar temperature and vacuum would require a large environmental chamber. If vehicle/soil interrelationships are to be thoroughly investigated, such a facility would be very large, expensive and, perhaps, not available early enough for timely testing of the assembled full scale system. On the other hand, critical full scale components (wheels, dampers, drive gears, etc.) can readily be tested to determine the affect of simulated lunar temperatures and vacuum on such aspects as spring and damping characteristics, frictional properties, and thermal transfer relationships. This approach is recommended with the stipulation that full scale testing to investigate vehicle/soil interrelationships be deferred until a sufficiently large simulation facility is available. At this time, such testing of the Locomotion System could be conducted concurrently with integrated tests of the complete MOLAB. Consequently, the development test program evolved during this study is inclusive of environmental tests only as they apply to critical full scale components.

In accordance with the foregoing discussion, it is suggested that component testing be employed to obtain full scale steady state and dynamic performance data both with respect to ambient atmospheric conditions and the anticipated thermal-vacuum-gravitational environment of the Moon. The following types of test equipment are recommended for this purpose:

o Force Ram Test Rig

The equation describing the motion of a spring-mass-damper system when acted upon by an external force is

$$M \ddot{x} + \bar{c} \dot{x} + \bar{k} x = F$$

where M is the mass, \bar{c} is the damper constant and \bar{k} is the spring constant.

If the force, the mass, and the spring constant are known, the damper constants for suspension systems and flexible wheels can be determined from

$$\bar{c} = \frac{F - M \ddot{x} - \bar{k} x}{\dot{x}}$$

Since the magnitude of the damping force varies with the velocity at which the load is applied, laboratory equipment for determining damping characteristics must employ dynamic forces. The force ram components tester shown in Figure 3 is an example of such equipment. Acceleration and velocity can be measured with an accelerometer and an integrating device, while the amplitude and frequency of the exciting force are varied over the range of values which encompass those anticipated for the operational system. The force, deflection, acceleration, and rate of deflection must be measured instantaneously. From these readings, the damping can be determined for the particular velocity measured. The sketch of Figure 3 represents a laboratory setup which can be used to determine the damper constants of flexible wheels or suspension systems. The sketch depicts a flexible wheel; however, a suspension system may be substituted for the wheel to obtain its damping characteristics. The two can also be combined and tested in series, if desired. The same testing could be used to determine spring constants by applying static loads with the force ram and measuring these loads for each increment of deflection.

o Components Testers

Steady state testing of full-scale wheels has been reasonably well standardized through the use of conventional soil bin testing methods. This is not true with respect to dynamic testing. The two types of tests are covered separately below.

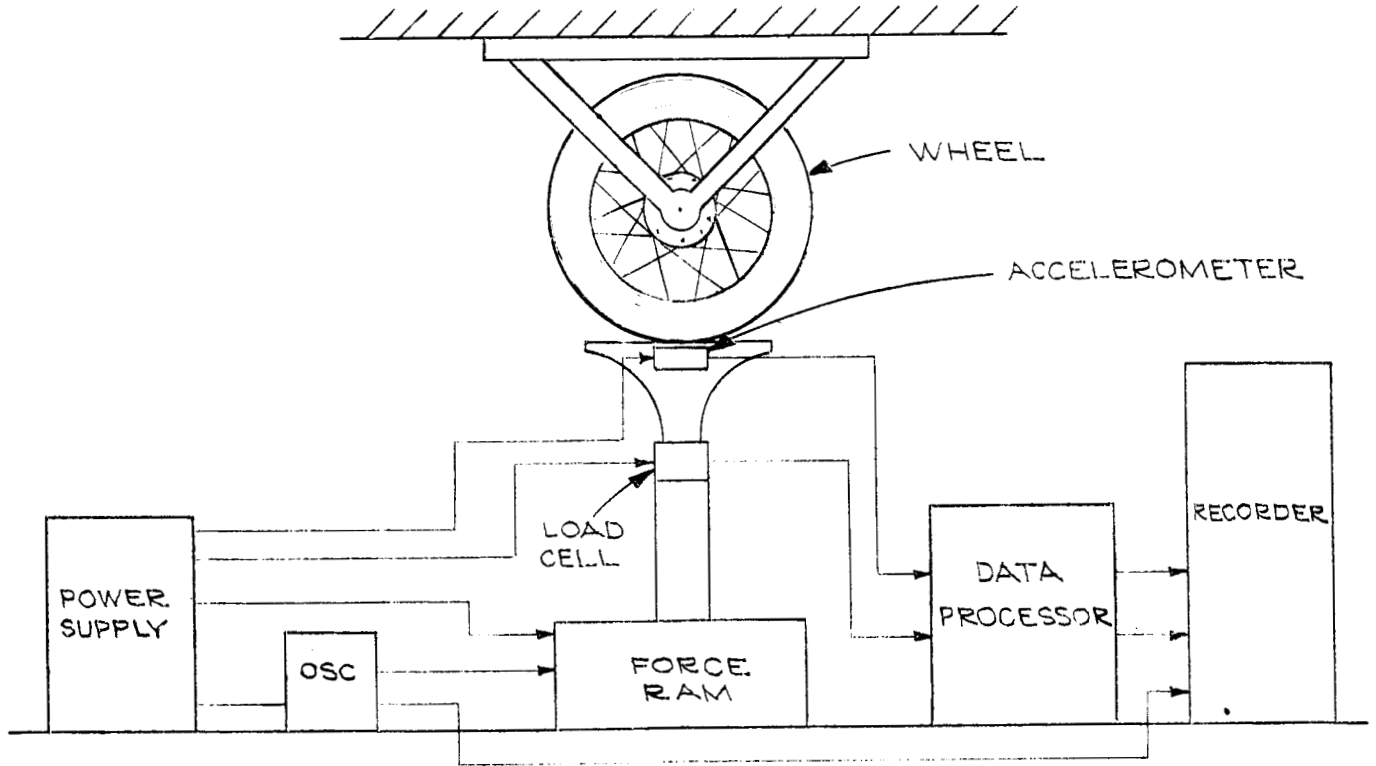


FIGURE 3. FORCE RAM (COMPONENTS TESTER)

Steady State Testing

Figure 4 shows a typical test setup for obtaining the steady state performance of full-scale wheels (Item 3 of the recommended test approach - Table 2). Tests would be made under ambient atmospheric conditions with the wheel load applied vertically through the axle by means of a weighted platform. The loaded wheel would be towed in a straight line over a soil bin equipped with the postulated lunar soils or hard surfaces. Instrumentation would be that required for measurements of drawbar pull, slippage, sinkage, rolling resistance, etc.

Dynamic Testing (Wheels and Suspensions)

Careful simulation of lunar gravity is required if the results of earth tests conducted on the wheels and suspension units (full scale) of lunar surface vehicles are to be valid for lunar operation. Accurate gravity simulation is particularly critical for large non-linear excursions during which the wheels may lose contact with the surface and the various spring elements may unload for short periods.

A possible technique for accomplishing this simulation is the use of a rotating arm (see Figure 5) equipped with a vertical loading platform and a circular roadway (properly surfaced and/or equipped with obstacles and slopes). The geometry of the test structure and the position and magnitude of the applied load must be so adjusted that the following conditions are satisfied:

1. The natural frequencies of the test system and the lunar surface vehicle are equal.
2. The static loads and displacements in the wheels and suspension units being tested are the same as those experienced by the corresponding elements of the lunar surface vehicle.

A preliminary analysis of the design approach for this type of simulator has been made by Mr. Lifer of the Vibration and Acoustics Branch of the P and VE Laboratory (see Reference 18). It is recommended that a detailed study be made of this type of facility with a view toward utilizing it for the dynamic testing of wheels and suspension units.

o Environmental Test Chamber

Components which can and should be tested under environmental conditions include: drive units, gear trains, bearings and seals, steering mechanisms, wheels and suspension units. Spring and damper characteristics of

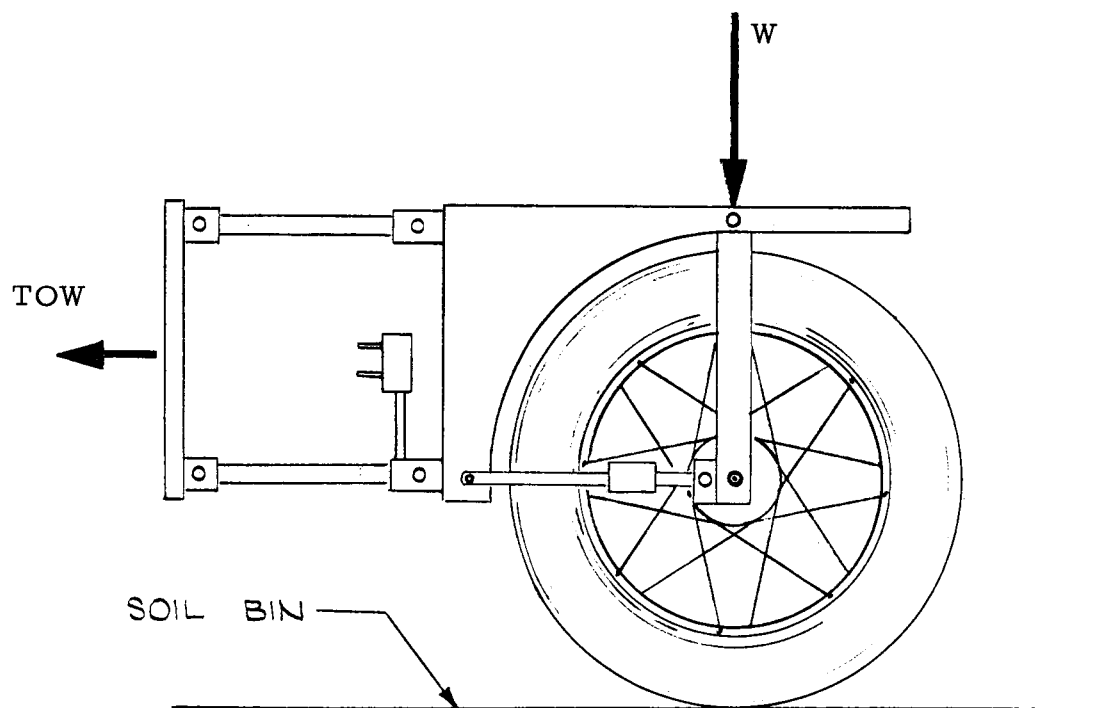


FIGURE 4. COMPONENTS TESTER - STEADY STATE

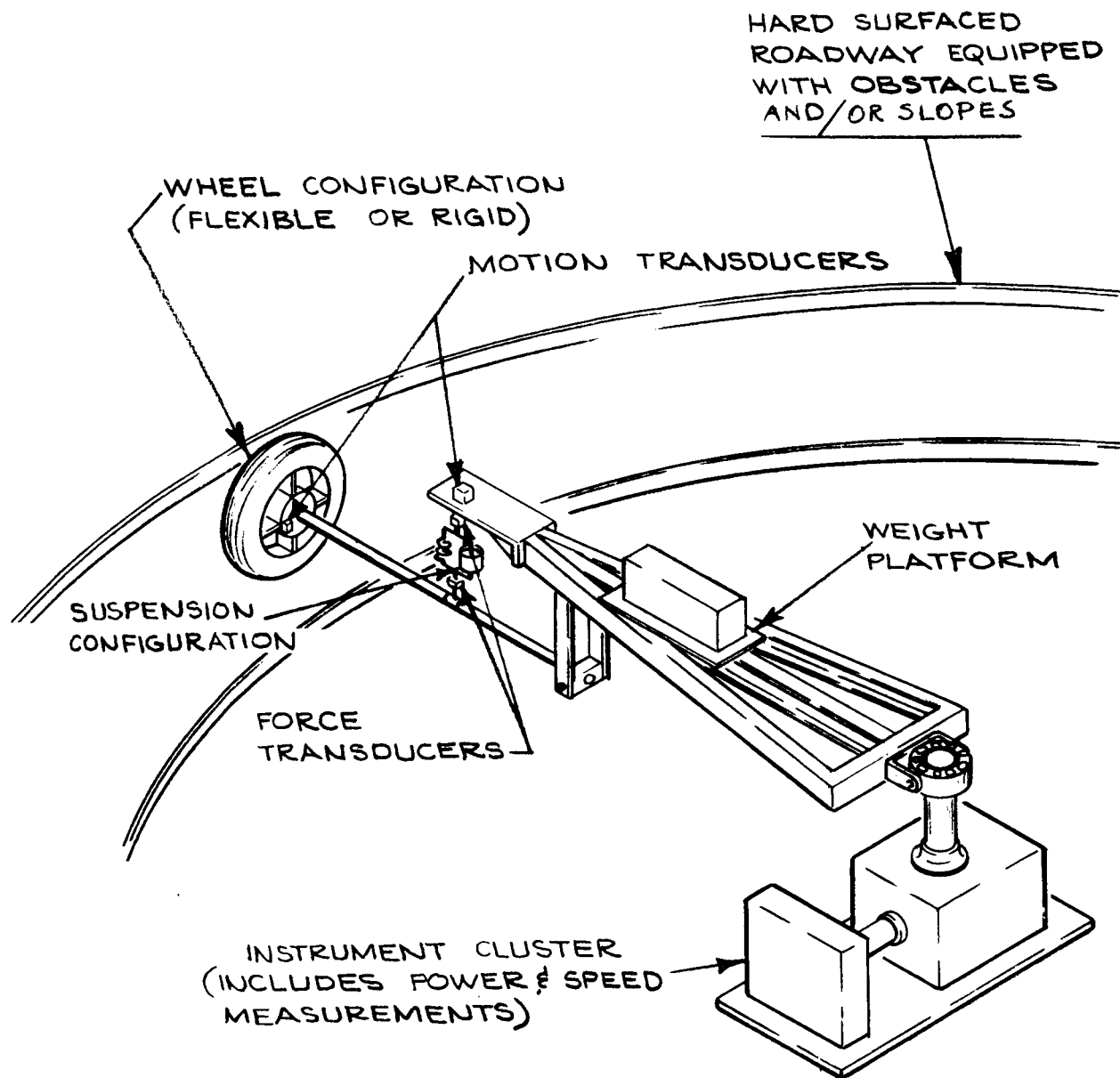


FIGURE 5. COMPONENTS TESTER - DYNAMIC

wheels and suspension units are likely to be affected by temperature and will require testing to determine these effects, along with frictional (resistance) properties. The other components make up the drive train and determine the internal resistance to vehicle movement. Wheel internal losses (bearing and flexure) and slippage can also be determined under environmental conditions on an individual component basis, as can the internal losses for drive units and gear train bearings.

Figure 6, below, represents a facility which can be used to conduct the required components testing under the extremes of lunar vacuum and temperature. A dynamic test is depicted in the sketch.

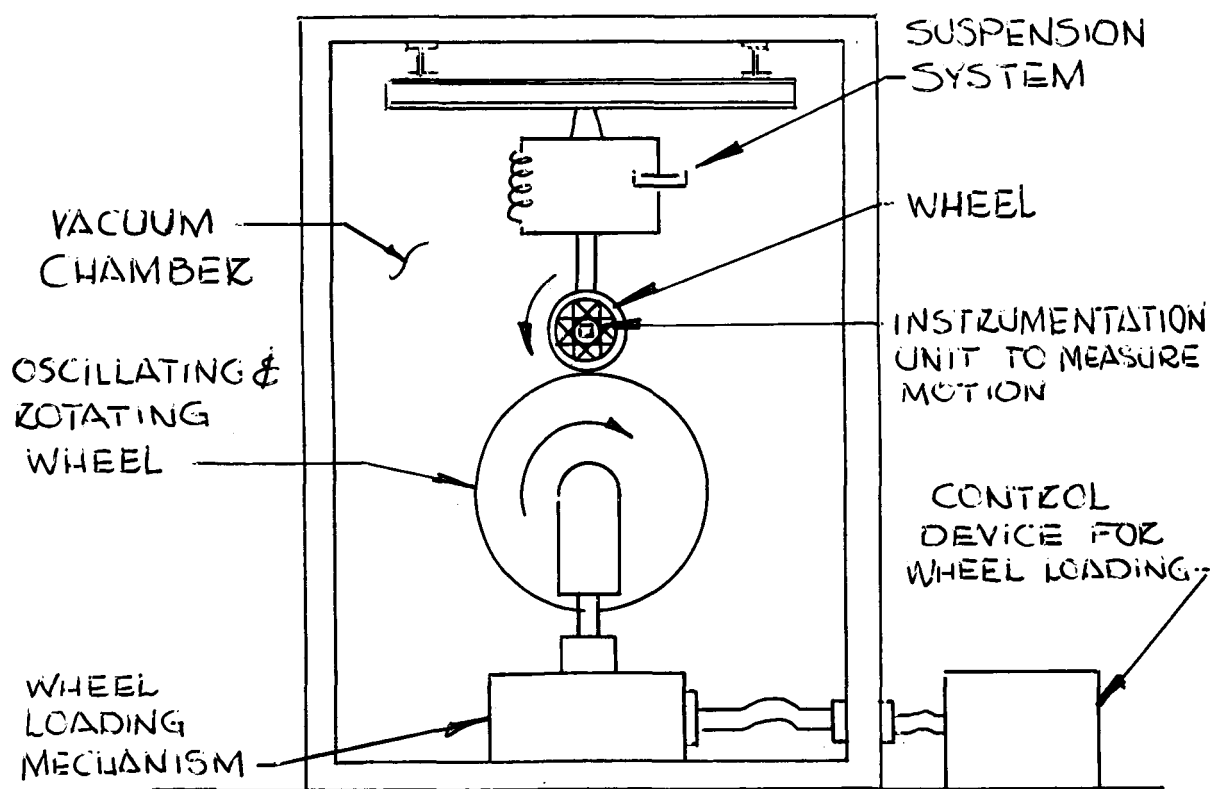


FIGURE 6. ENVIRONMENT TEST CHAMBER FOR COMPONENTS TESTING

7.3

TEST BED TECHNIQUE

Another testing technique which offers considerable promise is the use of a full size test bed, constructed to 1/6th the mass of an operational MOLAB. The test bed would accommodate all key components of candidate systems (wheels, axles, gears, suspension,

etc) as assemblies which would be tested at constant speeds to obtain comparative steady state performance data. Obstacle performance would be evaluated at $v \approx 0$. Use of this technique would make valid the steady state data thus obtained at the equivalent lunar weight (1/6th lunar mass) of the MOLAB. Comparison of such performance parameters as wheel thrust, drawbar pull, external resistance, sinkage, slippage, obstacle performance, and power would weigh heavily in the selection of the final subsystem concept.

Another useful application of the full size (1/6th mass) test bed is as a means to develop accurate methods of predicting the dynamic response of the vehicle to lunar surface perturbations. Assuming valid equations of motion can be written for the vehicle, the spring and damper constants and other relationships obtained from the component tests can be incorporated in the equations and the response of the system to dynamic excitation in the Earth's gravitational field can be predicted by use of a computer. Proper instrumentation of the vehicle will provide data for comparing its response with that predicted by the computer simulation using Earth constants. If agreement is not obtained, the equations of motion can be modified using successive iterations, until agreement is reached. When verification is obtained, dynamic response on the Moon can be predicted with reasonable confidence by using Moon constants rather than Earth constants in the computer simulation. The test data obtained during this process can also be used as parametric data for comparing the different design concepts operating in the Earth's gravitational field.

A similar test bed, ballasted to the equivalent lunar mass (6 times lunar weight) of the MOLAB could be used to obtain limited comparative dynamic performance data. Directional (sliding) stability during braking (all modes) as well as sliding stability, during turns (level surfaces and slopes) can be investigated if tests are conducted on a smooth hard surface for which the coefficient of friction has been reduced to 1/6th that expected for smooth hard surfaces on the Moon. As proof of this, consider the case of sliding friction for Newton's equation in the form $\mu W = M\alpha$. If the mass of the model (M_m) and prototype (M_p) are equal, the sliding characteristics of both model and prototype are dynamically equivalent if the left hand side of this equation is equal for both, i. e., $(\mu W)_m = (\mu W)_p$. Since $W_p = W_m(1/6)$, this equivalence holds if the surface over which the vehicle operates has a coefficient of sliding friction 1/6th of that postulated for the Moon.

Certain problems are presented by such tests. The weight applied to such components as the suspension system, wheels and bearings is six times that to be experienced during lunar operations. Consequently, if prototype components are used, overloading during testing might lead to failures. Also, the increased static deflection of prototype suspension units would, to some extent, affect sliding stability and braking performance.

It appears advisable, therefore, to conduct such tests without suspension units. Special wheels could be used, if overloading is anticipated; however, tire material would have to be the same as for the prototype to establish the proper relationship for sliding friction. It is believed that the resulting data would be valuable, but might best be treated as qualitative for comparison of concepts. It should be noted that (except for the effect of lunar gravity on the driver) the astronauts could also be indoctrinated in MOLAB handling characteristics during such simulated maneuvers. Further analysis should be accomplished before deciding the advisability of full-size-full-mass tests.

A test bed concept, suitable for the preceding tests, is depicted in Figure 7. Tests 5 and 6 of Table 2 are representative of typical tests for the employment of this vehicle. Attention is again called to Figure 1 which shows the unitized (multi-wheeled) and segmented vehicle concepts. In connection with these concepts, it should be noted that the preceding discussion is equally valid in application.

7.4 FIELD TESTS OF FINAL CONFIGURATION

Following completion of the preceding tests, a final system configuration should be selected and design changes incorporated. Prior to conducting tests under simulated lunar gravity, field tests should be run with such a system. These tests would be made in an area (or areas) which approximates as closely as possible the anticipated extremes of lunar surface conditions, e.g., lava flows, volcanic ash, sand and various combinations of each. Some changes may be advisable in the final locomotion configuration as a consequence of such field tests.

7.5 FINAL SYSTEM TESTS (SIMULATED LUNAR SURFACE AND GRAVITY)

The final consideration (exclusive of system thermal-vacuum tests) in the development of the Locomotion System is that of test verification of dynamic mobility parameters under simulated lunar gravity conditions. Two major possibilities were considered during the study. These are as follows:

- o Suspension (5/6th Mass)

A large traveling support system, preferably maneuverable, coupled with a test roadway over which the suspended vehicle operates can be used to simulate lunar gravity. The overhead system supports 5/6ths of the unsprung mass of the vehicle and maintains a constant lifting force as the Locomotion System is dynamically

Note: Accommodates full size components (assembled as complete, or essentially complete, for comparative evaluation of concepts and final selection of system

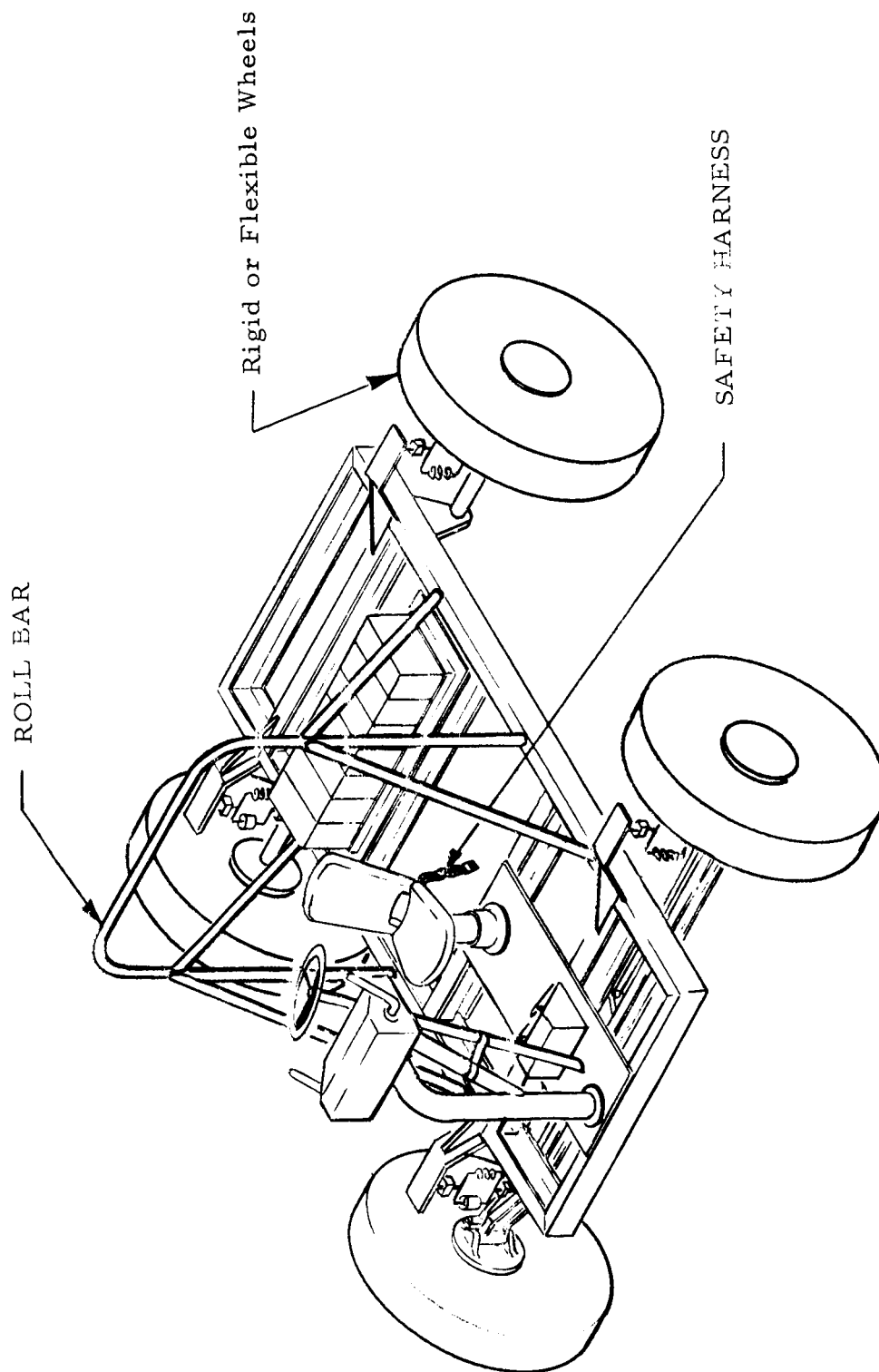


FIGURE 7. TEST BED CONCEPT - 4 WHEELED UNITIZED VERSION

perturbed. This effect could be accomplished by a very long soft spring (or a "Negator" spring) which applies a negligible force variation to the unsprung mass, when disturbed, or by a fast response servo type suspension mechanism.

Worst case conditions would be simulated for obstacles by combining them with a hard surfaced roadway. Dynamic stability during turns on level surfaces (hard and soft-with or without obstacles) can also be investigated, if the vehicle support mechanism is fast in its response and is also maneuverable along any vector in the horizontal plane while maintaining its constant 5/6th Earth gravity lifting force. Tests during climbing or descent would, of course, be impractical. In addition, steady state data can also be obtained with this test system under very good conditions of gravity simulation with either a full-scale, full mass test bed, or the final prototype hardware. This method is versatile (applicable to both dynamic and steady state performance tests), and provides good gravity simulation for the unsprung mass, but has the disadvantages of design complexity and high cost. Another disadvantage is that the wheels, axles and all other integral components of the sprung mass are not subjected to the correct gravity environment. This could be accomplished, however, by also suspending 5/6ths of the mass of the wheels - a further complication of added cost. Figure 8 is a schematic of the type of facility envisioned for this technique of simulating lunar gravity.

o Inclines

A straight plane inclined at 80.4 degrees to the horizontal with the vehicle restrained at its c. g. by a cable so that its longitudinal or lateral axis is parallel to the incline can also be used as a lunar gravity simulator for certain types of dynamic tests. As the vehicle moves longitudinally relative to the incline, its dynamic response to vertical exciting forces created by surface irregularities will closely simulate the response which it would experience under similar conditions on the lunar surface. An obstacle equipped incline-fixed or treadmill type - can be used for either orientation of the vehicle. Figure 9 shows two possible configurations.

The primary advantages of these types of inclines are their ability to provide quite accurate lunar simulation of (1) static forces throughout the system, and (2) dynamic properties of the sprung and unsprung masses. Disadvantages are (1) the difficulty of maintaining uniform relative motion along the vehicle's longitudinal axis as the system is perturbed in its vertical plane, (2) limited versatility, (3) practical

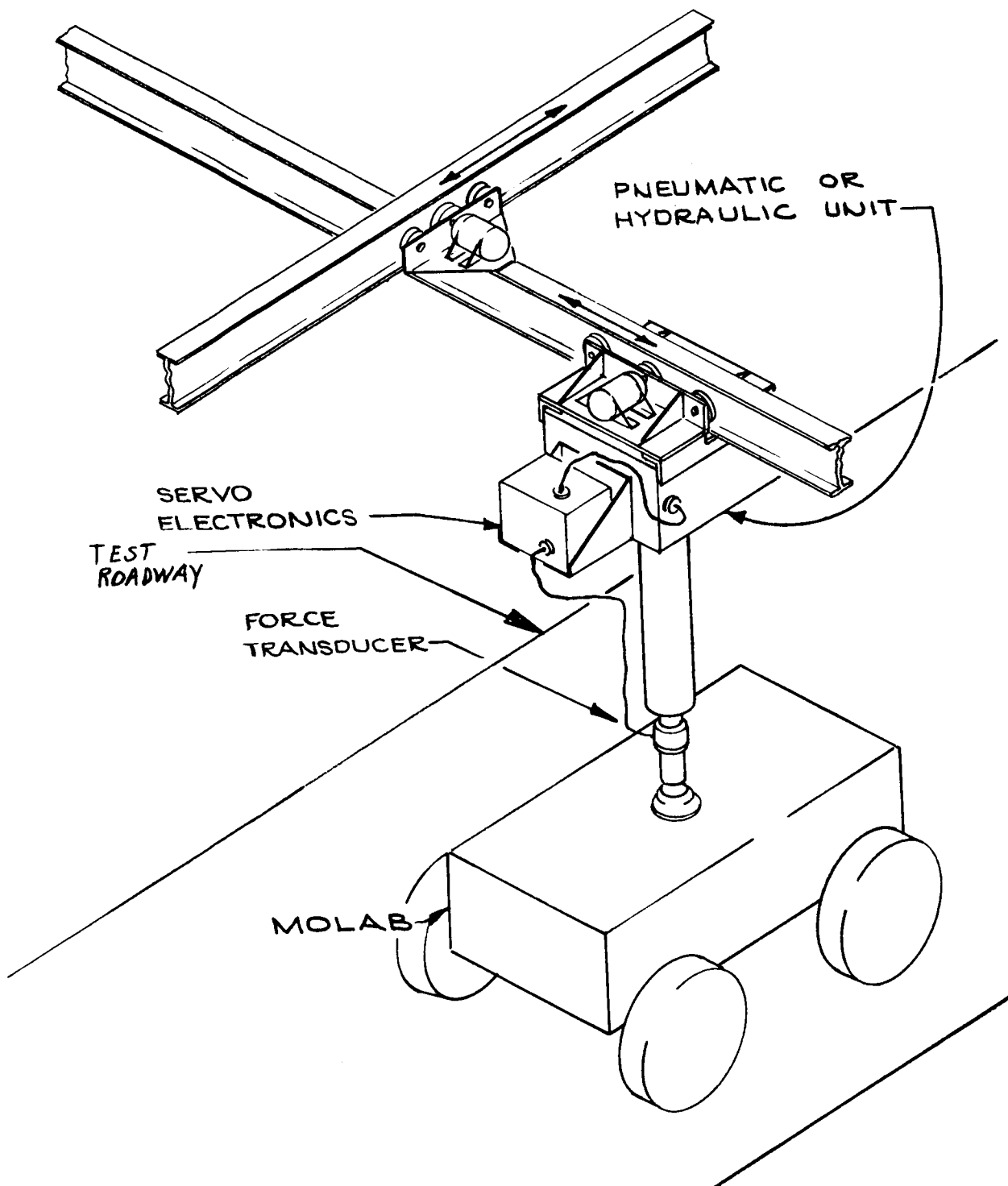
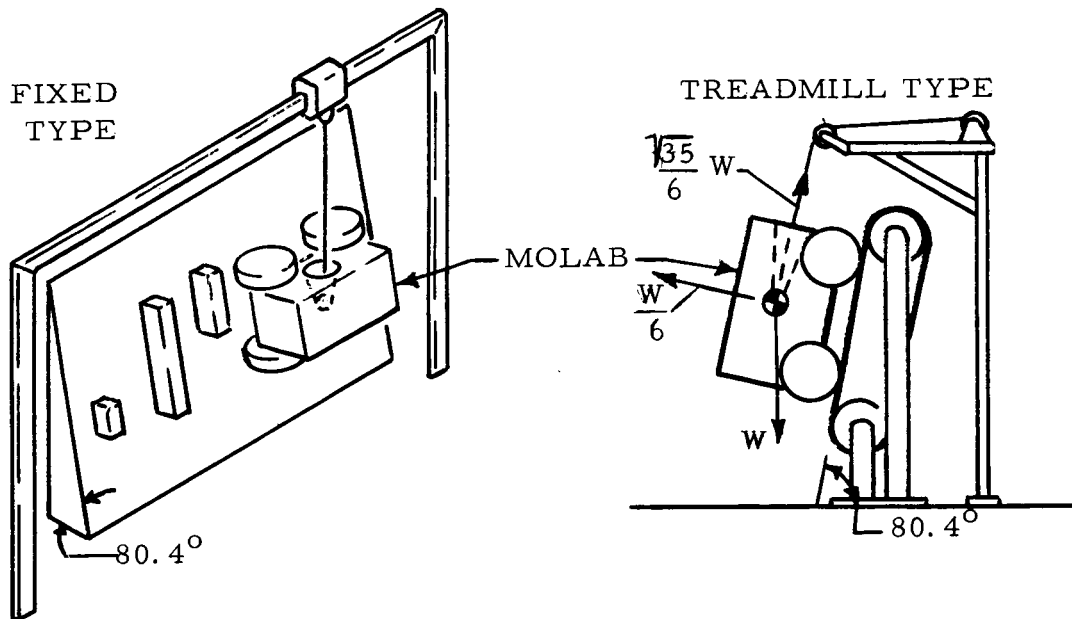


FIGURE 8. OVERHEAD SUSPENSION FACILITY 1/6th GRAVITY SIMULATOR

a. STRAIGHT PLANES



b. RIGHT CIRCULAR CONE FRUSTRUM
ENDLESS ROADWAY

(Equipped With Obstacles)

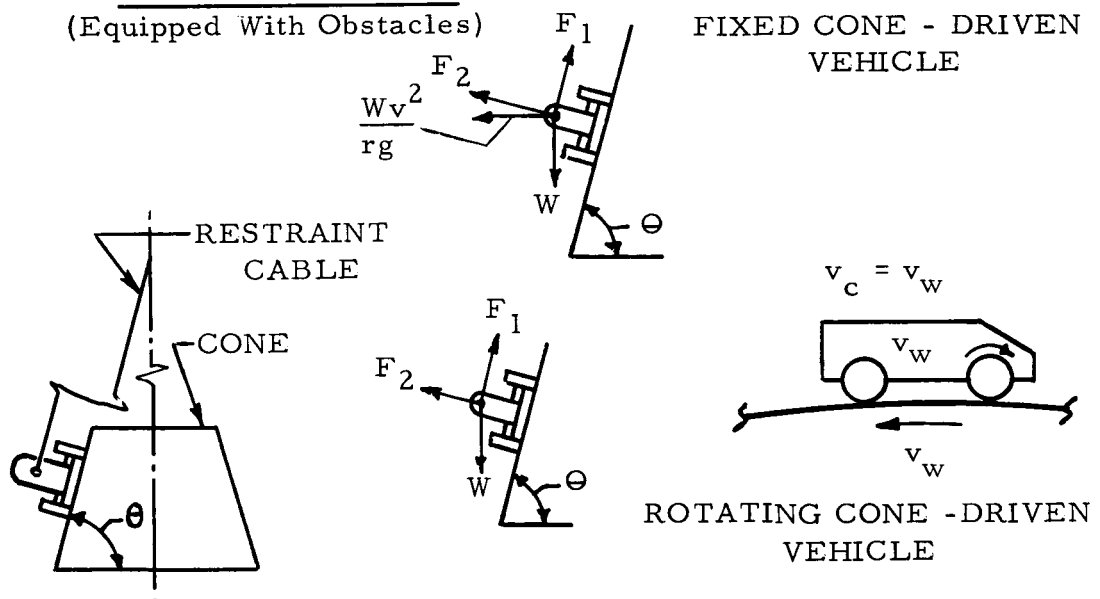


FIGURE 9. INCLINE TYPE - LUNAR GRAVITY SIMULATORS

limitations on the length of test run, and (4) for the treadmill facility- the difficulty of rigidizing the surface of the treadmill against flexure as the wheels of the vehicle impact against obstacles.

Figure 9b illustrates another type of incline-a right circular cone frustrum, the surface of which can be used as an endless runway for the vehicle which is restrained by a cable attached to its center of gravity. Two possible schemes for creating relative motion in the longitudinal direction are (1) rotation of the vehicle about the fixed cone, and (2) rotation of the cone and vehicle wheels at opposing equal velocities so as to create a vehicle velocity of zero relative to the ground (assuming no slippage). A preliminary analysis of several variations for the cone frustrum type facility is given in Appendix C. Conclusions relevant to this analysis are

1. The rotating cone and driven vehicle (scheme 2) is satisfactory for the conduct of tests designed to investigate the dynamic response of a vehicle to surface irregularities and is superior (see Appendix C) to incline facilities of the type represented in Figure 9a.
2. The fixed cone-rotating vehicle test configuration (scheme 1) is adversely affected by centrifugal force which, at the higher velocities, appreciably reduces the magnitude of the gravity simulation vector (See Appendix C, Figure C-2).
3. Design problems associated with the use of this type of facility for the investigation of stability and handling characteristics are more difficult to resolve. However some aspects of this possible extension of test usage appear sufficiently promising to warrant further study.

o Recommended Facility

The 5/6th mass overhead suspension system (Figure 8) is more versatile than any of the incline type facilities discussed above. If properly designed, it appears that it can be used for steady state testing (using various simulated lunar soils) as well as for a wide variety of dynamic testing. Although certain steady state tests could be performed on inclines, these could only be conducted on hard surfaces. As noted above, the scope of dynamic testing using an incline type facility can possibly be increased to include stability investigations

SECTION 8.0

TEST ARTICLES AND EQUIPMENT

Test articles and equipment for the development test program outlined in Table 2 are summarized in Appendix B, along with other information pertinent to their presentation. The results are considered as too detailed for inclusion in the text of the report; hence, the reader is referred to the Appendix for their review.

during maneuvers (sliding, tipping, etc.). However, such tests may be limited by practical considerations and further analysis is required before they can be given serious consideration.

Further investigations may indicate the advisability of constructing both the overhead suspension facility and an incline type facility. For example, the early availability of a rotating cone frustrum for investigating the vehicle's dynamic response to surface irregularities, as previously discussed, would greatly expedite the final design of the suspension system. The overhead suspension system would probably be considerably more expensive and require more time to develop but could be used for final dynamic and steady state tests of the integrated prototype configuration.

If the costs of an overhead suspension facility prove to be prohibitive, it might be desirable to develop a more versatile cone frustrum type facility for a broader range of dynamic testing. Pending the results of further investigations, the 5/6th mass overhead suspension facility is recommended for final demonstration of the vehicle's dynamic response and ride characteristics.

SECTION 9.0

CONCLUSIONS

The following conclusions are pertinent to the findings of this study:

1. The use of computer based, analytical programs is important for the early identification of promising concepts, as well as for investigating the effect of design changes at any stage of development.
2. Scale models may be utilized at an early stage of design to check comparative performance trends, eliminate the misfits among competing concepts, verify equations of motion, and obtain trend data for predicting prototype performance.
3. Tests of full scale components such as wheels and suspension systems should be accomplished at an early development stage to obtain detailed performance data to be used as the basis for (1) expediting the elimination of inadequate designs, (2) detecting and correcting design deficiencies of the more promising concepts, and (3) providing design inputs at interfaces with other MOLAB systems.
4. Critical components and assemblies should be subjected to environmental tests (thermal-vacuum-vibration) to determine the effect of environmental extremes on such items as seals, lubricants, damping, spring rates, long term storage, and fatigue life. These tests should be made on the full scale components and assemblies, prior to tests of the complete prototype system.
5. A full scale test bed constructed to 1/6th the mass of the operational MOLAB will provide valid steady state performance data for the system assemblies. When ballasted to full MOLAB mass, such a test bed may also be useful for obtaining qualitative data for comparison of sliding stability characteristics of competing designs (see discussion Paragraph 7.3).
6. Final testing of the selected prototype system concept should be made with some type of lunar gravity simulator. Such a simulator should be versatile enough to permit as realistic a determination of performance as is possible.

SECTION 10.0

RECOMMENDATIONS

As a result of the work performed during this study, a general approach to mobility testing of the MOLAB Locomotion Subsystem was evolved. In accordance with study findings, it is recommended that

1. Tests using small scale models be employed (where advisable) for the purpose of eliminating obvious misfits, to establish performance trends, and to validate the dynamic equations of motion.
2. Small scale models, intended for mobility testing, employ a 1/6th geometric relationship with the prototype vehicle and that dynamic models use prototype materials for those components which exercise critical constraints on the dynamic test results. For example, suspensions and flexible wheels for use during tests intended to establish base line data for transmissibility characteristics of different concepts should use prototype materials.
3. Comparative testing of the full scale components of competing design concepts be conducted to obtain detailed performance data as early in the development program as possible.
4. A full scale (1/6 mass) test bed be used to evaluate steady state performance characteristics of the system assemblies prior to the selection of the final design from among competing concepts. Other possible uses are discussed in the text.
5. Final testing of the prototype system employ a lunar gravity simulator-probably similar to the type shown in Figure 8.
6. Special test equipment and facilities be made available as early as possible for use in the development program--such items as are discussed in Section 7; namely
 - o Force Ram Test Rig - Figure 3
 - o Components Testers (Steady State and Dynamic) - Figures 4 and 5
 - o Mobility Test Bed (or Beds) -Figure 7
 - o Environment Test Chamber for Components - Figure 6
 - o Overhead Suspension Facility - Figure 8 (to be substantiated

by further analysis).

7. Further studies in depth be performed in the following areas:

o Facilities and Special Test Equipment

These studies are needed to further define and analyze design requirements for the facilities recommended in Item 6. For example, a more detailed analysis should be made before a final decision is reached regarding the type of lunar gravity simulator best suited to the needs of the test program (i. e., overhead support or incline type facility).

o Test Specifications and Procedures

These should be developed in some detail to support the design requirements of the preceding item and to assure the best use of planned facilities and equipment.

o Soil Research

Further work is needed in soil analysis and research to assure the availability of soils of required mechanical properties. Synthetic soils may be necessary for this purpose.

APPENDIX A

ANALYSIS
OF
SCALE MODEL TESTING
OF
LUNAR SURFACE VEHICLES

SCALE MODEL TESTING

Vehicles intended for lunar surface transportation are small relative to those for ships and aircraft. As a consequence, considerations such as cost and safety do not dictate as great a dependence upon the use of scale (small) models for their development as for the development of ships and aircraft. However, the use of scale models as a research tool does have a place in the scheme of lunar surface vehicle development. When coupled with an analytical, computer based program and full-scale testing of components, scale model testing can be used to advantage to speed development to prototype status and to reduce the costs attendant to the development program.

Scale model design and analysis, including the determination of scale relationships, is based upon the theory of similitude and utilize the techniques of dimensional analysis. Before considering the types of tests for which scale models of lunar surface vehicles are most suited it is, perhaps, advisable to establish the scale relationships (conversion factors) which must hold between the scale model and the prototype (full-scale) vehicle. This is accomplished in subsequent paragraphs.

VEHICLE/HARD SURFACE RELATIONSHIPS

Dynamic behavior of the vehicle is largely dependent upon inertia, gravity and friction as they relate to the interface between the vehicle and the surface over which it operates. The surface may be hard, in which case surface friction is the important interface relationship, or it may be soft, for which condition basic soil constants are the key interface considerations. Consider the first of these two cases, i.e., a hard surface. Using the Newtonian System and assuming geometric similarity, the following dimensional matrix can be set up:

	L	F	v	I	ρ	P	HP	N	g	μ
M	0	1	0	1	1	1	1	0	0	0
L	1	1	1	2	-3	-1	2	0	1	0
T	0	-2	-1	0	0	-2	-3	-1	-2	0

where the variables are

L = length	ρ = mass density	N = rpm
F = force	P = contact pressure	g = gravity
v = velocity	HP = horsepower	S = travel distance
I = inertia	μ = friction coefficient	

Let ρ , L, and g be the base variables and select v as the dependent variable. By means of dimensional analysis, the following equation can be written:

$$\frac{v^2}{gL} = f \left[\frac{F}{\rho g L^3}, \frac{I}{\rho L^5}, \frac{P}{\rho g L}, \frac{HP^2}{\rho^2 g^3 L^7}, \frac{N^2 L}{g}, \frac{S}{L}, \mu \right] \quad (1)$$

For theoretical validity in scale model tests, the following relationships must hold:

$$\left(\frac{F}{\rho g L^3} \right)_m = \left(\frac{F}{\rho g L^3} \right)_p \quad (2) \quad \left(\frac{HP^2}{\rho^2 g^3 L^7} \right)_m = \left(\frac{HP^2}{\rho^2 g^3 L^7} \right)_p \quad (5)$$

$$\left(\frac{I}{\rho L^5} \right)_m = \left(\frac{I}{\rho L^5} \right)_p \quad (3) \quad \left(\frac{N^2 L}{g} \right)_m = \left(\frac{N^2 L}{g} \right)_p \quad (6)$$

$$\left(\frac{P}{\rho g L} \right)_m = \left(\frac{P}{\rho g L} \right)_p \quad (4) \quad \left(\frac{S}{L} \right)_m = \left(\frac{S}{L} \right)_p \quad (7)$$

$$(8) \quad \mu_m = \mu_p$$

Where the subscripts "m" and "p" refer to model and prototype if these conditions hold, Froude's number must also be invariant, i.e.,

$$\left(\frac{v^2}{gL} \right)_m = \left(\frac{v^2}{gL} \right)_p \quad (9)$$

Let contact pressures be equal, i.e., $P_m/P_p = 1$ and let $L_p/L_m = \lambda$

From equation (4)

$$\frac{\rho_m}{\rho_p} = \left(\frac{P_m}{P_p} \right) \left(\frac{g_p}{g_m} \right) \left(\frac{L_p}{L_m} \right) = \lambda \left(\frac{g_p}{g_m} \right) \quad (10)$$

from equation (2)

$$\frac{F_m}{F_p} = \frac{1}{\lambda^2} \quad (11)$$

from equation (3)

$$\frac{I_m}{I_p} = \left(\frac{1}{\lambda^4} \right) \left(\frac{g_p}{g_m} \right) \quad (12)$$

substituting $I = ML^2$ (L = radius of gyration) in equation (12), we have

$$\frac{M_m}{M_p} = \left(\frac{1}{\lambda^2} \right) \left(\frac{g_p}{g_m} \right) \quad (13)$$

from equation (5), (6), (7), (8), (9), and (13), we have

$$\frac{HP_m}{HP_p} = \left(\frac{1}{\lambda^{5/2}} \right) \left(\frac{g_m}{g_p} \right)^{\frac{1}{2}} \quad (14) \quad \frac{v_m}{v_p} = \left(\frac{1}{\lambda^{\frac{1}{2}}} \right) \left(\frac{g_m}{g_p} \right)^{\frac{1}{2}} \quad (17)$$

$$\frac{N_m}{N_p} = \lambda^{\frac{1}{2}} \left(\frac{g_m}{g_p} \right)^{\frac{1}{2}} \quad (15) \quad \mu_m = \mu_p \quad (18)$$

$$\frac{S_m}{S_p} = \frac{1}{\lambda} \quad (16) \quad \frac{W_m}{W_p} = \frac{1}{\lambda^2} \quad (19)$$

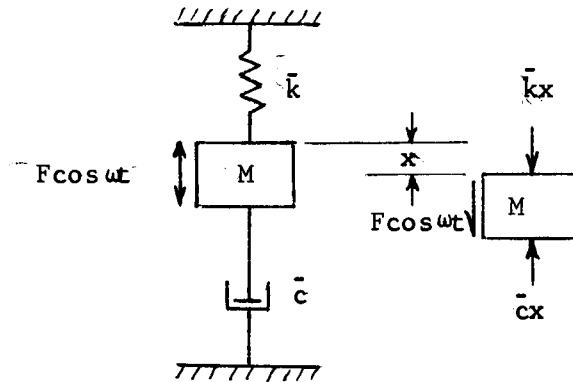
from equations (16 and 17) and the relationship $v = S/t$, we obtain

$$\frac{t_m}{t_p} = \left(\frac{1}{\lambda^{\frac{1}{2}}} \right) \left(\frac{g_p}{g_m} \right)^{\frac{1}{2}} \quad (20)$$

The preceding relationships are (where influenced by changes in gravity) expressed in terms of gravity for later conversion, i.e., earth model to earth prototype or earth model to lunar prototype.

Let us now determine the scale factors which must hold for spring constants, damping constants and frequency of vibration. Consider the simplified, single degree of freedom system shown below. Assuming the spring to be linear and the damping of the dashpot to be viscous, it is evident from the free body diagram of the mass that the following variables are pertinent to the motion of the system:

x	displacement	L
M	mass	M
\bar{c}^*	damping	MT^{-1}
\bar{k}^*	spring constant	MT^{-2}
t	time	T
F	applied force	MLT^{-2}
ω	frequency	T^{-1}



If F , L and M are considered as the base variables and \bar{k} as the dependent variable, the following equation can be written:

$$\left(\frac{L}{F} \right) \bar{k} = f \left[\frac{\bar{c}t}{M}, \frac{Ft^2}{LM}, \omega t \right]$$

or

$$\left(\frac{L}{F} \right) \bar{k} = f \left[\frac{\bar{c}t}{M}, \frac{\bar{k}t^2}{M}, \omega t \right], \text{ since } \bar{k} = \frac{F}{L}$$

For validity, the following must hold for scale model tests:

$$\left(\frac{L}{F} \bar{k} \right)_m = \left(\frac{L}{F} \bar{k} \right)_p \quad (21) \quad \left(\frac{\bar{k}t^2}{M} \right)_m = \left(\frac{\bar{k}t^2}{M} \right)_p \quad (23)$$

$$\left(\frac{\bar{c}t}{M} \right)_m = \left(\frac{\bar{c}t}{M} \right)_p \quad (22) \quad (\omega t)_m = (\omega t)_p \quad (24)$$

* These designations used to prevent confusion with soil characteristics.

from equation (21)

$$\frac{\bar{k}_m}{\bar{k}_p} = \frac{F_m}{F_p} \cdot \frac{L_p}{L_m} = \frac{1}{\lambda} \quad (25)$$

from equations (22) and (24)

$$\frac{\bar{c}_m}{\bar{c}_p} = \left(\frac{1}{\lambda^{3/2}} \right) \left(\frac{g_p}{g_m} \right)^{1/2} \quad (26)$$

$$\text{and } \frac{\omega_m}{\omega_p} = \frac{t_p}{t_m} = \lambda^{1/2} \left(\frac{g_m}{g_p} \right)^{1/2} \quad (27)$$

VEHICLE/SOFT SURFACE RELATIONSHIPS

For a system of rigid wheels, operating (towed) in non-viscous deformable soil, consider the following variables:

L = lengths (all)	c = cohesion coefficient
F = applied force	E = soil modulus of elasticity
r = soil particle size	ρ = soil mass density
g = gravity	μ = coefficient of friction
ϕ = soil friction angle	k = mod. of soil def. = $\frac{k_c}{b} + k_\phi$
R = motion resistance resulting from soil compaction	v = velocity

If F, ρ and L are base variables and R is a dependent variable, the equation for R can be written as:

$$\frac{R}{F} = f \left[\mu, \phi, \frac{r}{L}, \frac{cL^2}{F}, \frac{EL^2}{F}, \frac{v^2 \rho L^2}{F}, \frac{\rho g L^3}{F}, \frac{kL^{n+2}}{F} \right] \quad (28)$$

From equation (28),

$$\frac{R_m}{R_p} = \frac{F_m}{F_p} \quad (29)$$

Rolling resistance (R), for rigid, towed wheels operating in deformable soils can be expressed as

$$R = AW^{\frac{2n+2}{2n+1}} \left(\frac{1}{bkd^{n+1}} \right)^{\frac{1}{2n+1}} \quad (30)$$

where

$$A = \frac{1}{(n+1)} \left[\frac{3}{3-n} \right]^{\frac{2n+2}{2n+1}}$$

From equation (30)

$$\frac{R_m}{R_p} = \left(\frac{W_m}{W_p} \right)^{\frac{2n+2}{2n+1}} \left(\frac{b_p d_p^{n+1}}{b_m d_m^{n+1}} \right)^{\frac{1}{2n+1}} \left(\frac{k_p}{k_m} \right)^{\frac{1}{2n+1}}$$

Reducing to dimensional form and substituting

$$W_m/W_p = 1/\lambda^2 \quad \text{and} \quad L_p/L_m = \lambda, \quad \text{we have}$$

$$\frac{R_m}{R_p} = \left(\frac{1}{\lambda} \right)^{\frac{3n+2}{2n+1}} \left(\frac{k_p}{k_m} \right)^{\frac{1}{2n+1}} \quad (31)$$

From equation (28)

$$\left(\frac{kL}{F} \right)_m^{n+2} = \left(\frac{kL}{F} \right)_p^{n+2}$$

or

$$\frac{F_m}{F_p} = \frac{k_m}{k_p} \left(\frac{L_m}{L_p} \right)^{n+2} = \left(\frac{1}{\lambda} \right)^{n+2} \left(\frac{k_m}{k_p} \right) \quad (32)$$

Equating equations (31) and (32) and solving for k_m/k_p

$$\frac{k_m}{k_p} = \lambda^n \quad (33)$$

$$\frac{F_m}{F_p} = \frac{1}{\lambda^2} \quad \text{and} \quad \frac{R_m}{R_p} = \frac{1}{\lambda^2} \quad (34)$$

From equation (28)

$$\left(\frac{\rho g L^3}{F} \right)_m = \left(\frac{\rho g L^3}{F} \right)_p \quad (35)$$

or

$$\frac{\rho_m}{\rho_p} = \frac{F_m}{F_p} \left(\frac{L_p}{L_m} \right)^3 \left(\frac{g_p}{g_m} \right) = \lambda \frac{g_p}{g_m} \quad (36)$$

From other relationships of equation (28), we find, for lunar soils

$$\begin{aligned} \mu_m &= \mu_p & \frac{E_m}{E_p} &= 1 \\ \phi_m &= \phi_p & \frac{v_m}{v_p} &= \left(\frac{1}{\lambda^{\frac{1}{2}}} \right) \left(\frac{g_m}{g_p} \right)^{\frac{1}{2}} \\ & & \frac{r_m}{r_p} &= \frac{1}{\lambda} \end{aligned}$$

Since $\gamma = \rho g$ = Specific weight of soil, we have from equation (35)

$$\frac{W_m}{W_p} = \frac{F_m}{F_p} = \frac{1}{\lambda^2}$$

also

$$\frac{M_m}{M_p} = \frac{1}{\lambda^2} \left(\frac{g_p}{g_m} \right), \quad \text{since } W = Mg.$$

USE OF CONVERSION RATIOS

The foregoing relationships may be considered as ratios for use in converting model test results to predicted prototype performance or for determining required test inputs (prototype equivalents) to the model. Table A-1 lists the previously developed relationships, along with others of an essentially obvious nature, the proof for which is omitted for the sake of brevity. The table presents the conversion ratios (model value to prototype value) in the following categories:

- (1) general with respect to gravity to allow for consideration of differing gravity fields for the model and prototype,
- (2) gravity invariant, e.g., earth model and earth prototype ($g_m = g_p$).
- (3) gravity variant for the specific case of earth model and lunar prototype,
- (4) gravity variant as in (3), but using a full-scale vehicle constructed to one-sixth the mass of the prototype vehicle.

The results in categories (2) and (3), columns (2) and (3) of Table A-1 are given for any scale ($L_m/L_p = 1/\lambda$) and, as an example, for the scale of 1/6, i.e., $\lambda = 6$. As an example of the use of the table, consider the second column of category (3). Assuming geometric similarity for the scale shown, i.e., $L_m/L_p = 1/6$, all experimental inputs and results for the model tests must be divided by the ratios given to convert to lunar prototype equivalent properties and expected lunar prototype results.

Column (4) was included to cover the special case of a full-size test bed (Mobility Test Bed) which, when constructed to 1/6th the mass of an operational MOLAB, would make possible the steady state testing of the Locomotion System. The use of such a test bed is discussed in the text of this report under Paragraph 7.3.

SELECTION OF SCALE

Mobility testing of the Locomotion Subsystem has been categorized (for the purpose of this study) as either dynamic or steady state. The size of model most appropriate for use with each type of test is discussed in subsequent paragraphs.

Dynamic Models

Consider the dimensionless ratio of equation (4)

$$\left(\frac{P}{\rho g L} \right)_m = \left(\frac{P}{\rho g L} \right)_p$$

where (P) relates to such material properties as tensile and compressive strengths, shear modulus, Young's modulus, etc., and (ρ) is the mass density of the material. If the difference in gravitational fields (earth model to lunar prototype) is accounted for, this equation reduces to

$$\frac{P_m}{P_p} \frac{\rho_p}{\rho_m} = 6 \left(\frac{L_m}{L_p} \right) \quad (37)$$

If an arbitrary scale of 1/10 is adopted, equation (37) becomes

$$\left(\frac{P}{\rho} \right)_m = \frac{6}{10} \left(\frac{P}{\rho} \right)_p$$

Therefore, a material for the model must be selected such that its (P/ ρ) ratio is six-tenths that of the prototype. Thus, if the material for the model is of the same density as that for the prototype, the model's tensile and compressive strengths, shear strength, and all its elastic moduli must be six-tenths that of the prototype. A somewhat exotic type material would, therefore, be necessary for such critical model components as wheels, suspension systems, and chassis if (for example) the results of model tests are to be valid for estimating the dynamic response of the prototype Locomotion System when subjected to postulated lunar surface irregularities. A much more practical approach (particularly since special material needs might only be satisfied by an expensive materials research program) would be the use of identical material for both model and prototype for which

$$P_m = P_p$$

and

$$\rho_m = \rho_p$$

Since $g_m = 6g_p$, equation (37) becomes

$$\frac{L_m}{L_p} = \frac{1}{6}$$

Thus, it is highly desirable and, generally, economically advisable to use prototype materials and to conduct dynamic model tests with 1/6 scale models.

Steady State Models

In the preceding section, it was demonstrated that a 1/6th scale model (constructed of prototype materials) appears best for use in dynamic tests of lunar surface vehicles. An inspection of Colum (3) of Table A-1 will show that, for the 1/6th scale case, the model soil should have the same angle of internal friction (ϕ) as the lunar prototype soil, the same mass density (ρ), and the same elasticity (E) --but reduced (1/6th) grain size and an increased modulus of soil deformation ($k_m = 6^n k_p$). If 1/4 scale is considered, the model soil should again have the same values for ϕ and E . Reduced (1/4th) grain size and increased ($4^n k_p$) modulus of deformation should also hold, although these values are lesser than for the 1/6th scale. The soil mass density, however, should be reduced to two-thirds that of the prototype. In either case, the values of soil model grain size and modulus of deformation would require adjustment for theoretical adherence to similitude requirements. Soil research indicates that the effect of grain size can be neglected, provided the largest grains are small compared to the smallest detail of interest on the model. For fine grain soils and sands the effect of grain size can probably be neglected; however, if the surface to be simulated is gravel, this is probably not the case. The use of synthetic soils (e.g., pearlite) may permit adjustments in grain size (if the case warrants) and the values of k and ρ . In any event, further research leading to the proper cataloging of soils is required.

From the preceding discussion, it appears that the primary advantage of the use of 1/6 scale models for steady state testing is that the model soil would not require a different mass density than the prototype soil.

FINDINGS

In the foregoing analysis, appropriate ratios were developed for converting mobility test data obtained with small scale models of lunar surface vehicles to predicted prototype performance and for determining the required test inputs (prototype equivalents) to the model. The proper size of scale model for use in mobility tests (steady state or dynamic) was also derived analytically. It should be noted that the analysis is not complete since the effect on scale model testing of such factors as wheel drag and bulldozing, driven (powered) wheels, soil remolding and slippage have not been considered. Conclusions relative to the analysis are, as follows:

1. Dynamic behavior of a vehicle is primarily dependent upon inertia, gravity, and the vehicle/lunar surface interface. Accordingly, the conversion ratios developed in the analysis (Table A-1) must be properly understood and applied in the design of models (test vehicles and surfaces) and the use of model test results if prototype performance predictions are to be valid.

2. The use of 1/6th scale models ($L_m/L_p = 1/6$) is advisable for both dynamic and steady state tests for the following reasons:

- Dynamic Models

For tests with such models it was concluded reasonable to use prototype materials to avoid the problem of

- (a) obtaining exotic materials with density and strength characteristics which would satisfy the rigorous demands of similarity principles, or
- (b) using distorted models with the attendant problems of determining the proper corrections to be applied to the test results.

- Steady State Models

For these models, the use of a scale other than 1/6th introduces the added problem of obtaining a model soil of a density different from that of the postulated lunar soil. This conclusion is tentative and should be substantiated by further research since it is possible that this advantage may be deemphasized by other advantages attendant to the use of larger models, e.g., greater ease and accuracy of instrumentation. Although similitude laws call for scaling of the model soil, this condition is rationalized as unimportant, so long as the largest grains are small compared to the smallest detail of interest on the model.

3. A reduced scale model cannot faithfully reproduce all details of the working prototype. Cross sections cannot be accurately duplicated throughout and special power equipment and instrumentation must be added. Consequently, extreme care must be exercised in the use of ballast to produce the correct mass relationships between the model and prototype. In essence, geometric similarity is required with respect to maintaining such items as cg location and radii of gyration about the principal axes.

TABLE A-1
MODEL/PROTOTYPE CONVERSION RATIOS

VARIABLES	CONVERSION RATIOS - MODEL/PROTOTYPE					
	(1) GENERAL RELATIONSHIPS	(2) $g_m/g_p = 1$	(3) $g_m/g_p = 6$	(4) SCALE $1/6$	(5) SCALE $1/6$	(6) $M_m/M_p/6$
	SCALE $(\frac{1}{\lambda})$	SCALE $(\frac{1}{\lambda})$	SCALE $(\frac{1}{\lambda})$	SCALE $(\frac{1}{\lambda})$	SCALE $(\frac{1}{\lambda})$	SCALE $(\frac{1}{\lambda})$
Linear dimensions of mechanisms and surface features	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Mass density (ρ) of mechanisms and soil	$\lambda \left(\frac{g_p}{g_m} \right)$	λ	6	$\frac{\lambda}{6}$	1	$\frac{1}{6}$
Applied force (F), drawbar pull (DP), mechanisms and soil, etc.	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Mass of mechanisms and soil	$\frac{1}{\lambda^2} \left(\frac{g_p}{g_m} \right)$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{6\lambda^2}$	$\frac{1}{216}$	$\frac{1}{6}$
Inertia of mechanisms (I)	$\frac{1}{\lambda^4} \left(\frac{g_p}{g_m} \right)$	$\frac{1}{\lambda^4}$	$\frac{1}{1296}$	$\frac{1}{6\lambda^4}$	$\frac{1}{1776}$	$\frac{1}{6}$
Horsepower	$\frac{1}{\lambda^{3/2}} \left(\frac{g_p}{g_m} \right)^{1/2}$	$\frac{1}{\lambda^{3/2}}$	$\frac{1}{88}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	2.45
Travel distances, displacements, strain, etc.	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Wheel turning rate (assuming no slippage)	$\lambda^{1/2} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\lambda^{1/2}$	2.45	$(6\lambda)^{1/2}$	6	2.45
Frequency (forced or resonant vibration, and angular velocity) - of mechanical nature	$\lambda^{1/2} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\lambda^{1/2}$	2.45	$(6\lambda)^{1/2}$	6	2.45
Damping coefficient (\bar{c}) of wheels, suspensions, etc. (viscous only - not applicable to non-linear case).	$\frac{1}{\lambda^{3/2}} \left(\frac{g_p}{g_m} \right)^{1/2}$	$\frac{1}{\lambda^{3/2}}$	$\frac{1}{14.68}$	$\left(\frac{1}{6\lambda} \right)^{1/2}$	$\frac{1}{36}$	$\frac{1}{2.45}$
Spring constant (\bar{k}) of wheels, suspensions, etc. (linear springs assumed).	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Friction coefficient (μ), angle of soil internal friction (ϕ), slopes and angles (θ).	1	1	1	1	1	1
Grain size of soil (r)	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1
Modulus of soil deformation (k), since $c = 0$ for lunar soils, $k = k_0$ in column (3).	λ^n	λ^n	6^n	λ^n	6^n	1
Compaction rolling resistance (R) in soft soil, weight, etc.	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Contact pressure (P)	1	1	1	1	1	1
Contact Area	$\frac{1}{\lambda^2}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	$\frac{1}{\lambda^2}$	$\frac{1}{36}$	1
Cohesion of soil (c)	1	1	1	1	1	1
Material strength, Young's modulus, elastic limit	1	1	1	1	1	1
Time of travel, fatigue life, wear, etc.	$\frac{1}{\lambda^{1/2}} \left(\frac{g_p}{g_m} \right)^{1/2}$	$\frac{1}{\lambda^{1/2}}$	0.41	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{2.45}$
Velocity of travel	$\frac{1}{\lambda^{1/2}} \left(\frac{g_m}{g_p} \right)^{1/2}$	$\frac{1}{\lambda^{1/2}}$	0.41	$\left(\frac{6}{\lambda} \right)^{1/2}$	1	2.45
Sinkage (z_0)	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	$\frac{1}{\lambda}$	$\frac{1}{6}$	1

*For lunar soils, (c) can be assumed as zero.

APPENDIX B

TEST ARTICLES AND EQUIPMENT

TYPES OF SPECIAL TEST ARTICLES AND EQUIPMENT

Included herein is an outline of the types of special test articles and equipment needed for mobility development tests of the MOLAB Locomotion System. Test requirements (including schematics of test facilities - Figures 1 - 9) are covered in the test approach discussed in Section 7 and summarized in Table 2.

Specifically--that portion of the study requirement which is reported in this Appendix is the outline of types of test articles and equipment. An added proviso of the study was that the design of test articles and equipment was not required.

Wherever reference is made to soils under "Special Test Equipment" in the tabulations of this Appendix, Reference 16 is to be used as the basis for lunar soil postulation--unless subsequent investigations indicate otherwise.

All obstacle courses for dynamic tests are to be designed in accordance with Annex G of Reference 16. The following is an example of the conditions which might be imposed during a typical dynamic test:

SPEEDS - 0.5 1, 2, 3 and 5 kilometers per hour

POWERED WHEELS - Front only, rear only, all powered

SOIL CONDITIONS - All wheels same (Hard surface)
-Left wheels same but different from right wheels.

STEP DISTURBANCES

- Height = 0.05, 0.1, 0.2, 0.3, and 0.5 radius of wheels
- Approach Angle - Perpendicular, 60° and 30° .
(a. both wheels contact together - b. one wheel only)
- Inclines level, and 5° - 35° in 5° increments.
- Step Width - .05, .1, .2, .5, 1 and 2 wheel bases

RAMP DISTURBANCES

- Height - same as step
- Approach angles - same as step (wheel contacts--same as step)
- Inclines - same as step
- Ramp angles - 30° and 60°
- Width of top - same as step widths

SINUSOIDAL INPUTS

Phasing between left and right and front and rear wheels for perpendicular encounter

0° 45° 90° 180°

Amplitudes - same as step

Approach angles - same as step

1. STEADY STATE - SMALL SCALE (Hard Surface and Comparative Soft Surface Tests)

Purpose: To establish trend information for candidate wheel concepts and relative data on obstacle performance. Primarily to eliminate misfits and verify computer program.

Test Articles:

Vehicle: 1/6 Scale Model

Wheels: Various candidates; accurately scaled; external configuration duplicated; prototype materials preferred.

Chassis: General concept only; ground clearances accurately scaled.

Body: Only critical with respect to mass distribution and cg.

Special Test Equipment:

Soil Bin: Adaptable to use of deformable soils (various) and hard surfaces (various values of μ) slopes.

Loads Equipment: Variable horizontal load (drawbar pull) device.

Soil Distribution and Homogenizing Equipment.

Obstacles: 1/6th Scale, as specified.

Special Instrumentation:

As required for measurement of thrust, drawbar pull, slippage power, speed, sinkage, static obstacle performance, etc.

Environment:

Ambient, except for humidity regulation to maintain cohesionless soil.

2. DYNAMIC - SMALL SCALE TESTS

Purpose: To obtain qualitative evaluation of wheel concepts and trends; to eliminate obvious misfits; verify equations of motion used in simulation program.

Test Articles:

Vehicle: 1/6th Scale Model

Wheels: Various candidates; accurately scaled deflection and flexibility; prototype materials required.

Suspensions: As appropriate to concept; accurately scaled deflection and flexibility; prototype materials required.

Chassis: General concept only; rigidity preferred for base line data approach; prototype materials not required; ground clearances accurately scaled.

Body: Mass distribution, cg, and inertias (all degrees of freedom) are critical.

Special Test Equipment:

Test Surface: Hard; variable slope.

Obstacles: 1/6th scale; sizes and shapes, as specified; combined with hard surface for worst case conditions.

Special Instrumentation:

As required for determining dynamic response to surface irregularities; establish comparative limits (velocities and obstacle sizes) for various concepts.

Environment:

Ambient

3. **STEADY STATE COMPONENT TESTS** (See Figure 4 of Text for Schematic of Test Set-Up).

Purpose: To obtain comparative steady state performance data for candidate wheels and suspension systems identified as promising during small scale tests. Determine required design changes.

Test Articles: (Full Scale Components)

Wheels: Preliminary design concepts; accurately configured.

Suspension Systems: Preliminary design concepts; accurately configured.

Special Test Equipment:

Soil Bin: Adaptable for use as hard surface (various values) and with deformable soils.

Loading Platform: As shown in Figure 4.

Special Instrumentation:

As required, for determining steady state performance data for full scale wheels and suspensions (e.g., thrust, drawbar pull, external resistance, internal resistance, slippage and power vs vertical load and/or velocity, as appropriate). Includes cameras and other special instrumentation.

Environment:

Ambient atmospheric. Humidity control desirable to maintain cohesionless soil

4. DYNAMIC COMPONENT TESTS (See Figure 5 of Text for Schematic of Test Set-Up)

Purpose: To obtain comparative dynamic performance data for candidate wheels and suspension systems under simulated lunar gravity.

Test Articles: (Full Scale Components)

Wheels: Preliminary design concept; accurately configured.

Suspension Systems: Preliminary design concept; accurately configured.

Special Test Equipment:

Large circular roadway: Useable as hard surface (various μ values) with obstacles of various sizes and shape.

Rotating Test Rig: See Figure 5.

Special Instrumentation:

As required for measuring such quantities as relative displacements, forces transmitted to and through the suspension system and flexible wheel, and accelerations (See Figure 5).

Environment:

Ambient atmospheric

5. SYSTEM PERFORMANCE-STEADY STATE (See Figure 7 of Text for Schematic of Test Bed)

Purpose: To obtain comparative steady state performance data on components of several selected systems assembled as operational entities. Also, to identify design deficiencies, establish final design concept, and establish validity of equations of motion (see Text, Paragraph 7.3).

Test Articles:

Full scale wheels, axles, gears, suspensions, steering and drive units, etc. (preliminary design concepts-- accurately configured).

Special Test Equipment:

Test Bed: Constructed to 1/6th MOLAB mass; accommodates components as subsystem assemblies.

Test Roadbed or Field Test Area: Equipped with obstacles, as specified.

Special Instrumentation:

As required, for measurements of steady state parameters such as those for Test No. 3. These measurements taken at constant speeds to eliminate dynamic effects and make valid the data obtained at the equivalent lunar weight (1/6 lunar mass) of the MOLAB. Obstacle performance at $v \approx 0$. Instrumentation also as required for dynamic response.

Environment:

Ambient atmospheric.

6. SYSTEM PERFORMANCE - LIMITED DYNAMIC (See Figure 7 of Text for Schematic of Test Bed).

Purpose: To obtain comparative sliding stability performance on components of several selected systems assembled as operational entities, identify design deficiencies, and establish final design concept.

Test Articles: Same as for Test 6, except ballasted to total MOLAB mass (See Text, Paragraph 7.3).

Special Test Equipment: Same as for Test 6, except Test Bed is ballasted to total MOLAB mass; hard surfaced roadway; μ adjusted to 1/6 lunar value.

Special Instrumentation: As required for measurements of sliding stability.

Environment:

Ambient atmospheric.

Note: Further analytical work should be accomplished prior to the use of this technique because of the problems discussed in Paragraph 7.3.

7. ENVIRONMENTAL TESTS OF CRITICAL COMPONENTS (See Figure 6 of Text for Schematic of Test Set Up)

Purpose: To obtain environmental exposure data for demonstration of critical components suitability for operational environment of Moon. Also to determine and correct design deficiencies.

Test Articles:

Wheels, bearings, seals, axles, gears, drive units, suspension units, and steering units. All full scale preliminary design configurations.

Special Test Equipment:

Vacuum Chamber: Capable of less than 10^{-9} torr.
Temperature Range ($\sim 115 - 400^{\circ}\text{K}$)

Dynamic Exciter: Variable load application over wide range of frequencies and displacements.

Special Instrumentation:

As required for specialized conditions of testing.

Environment:

As indicated under "Special Test Equipment".

8. FIELD TESTS OF FINAL CONFIGURATION

Purpose: To obtain field test data for qualitative evaluation of performance and handling characteristics of Locomotion System.

Test Articles:

Vehicle: Complete Locomotion System; full scale prototype; operable MOLAB Power System desirable; other systems not necessary.

Special Test Equipment:

Test Area: Approximates extremes of lunar surface conditions; e.g., lava flows, volcanic ash, sand, and gravel.

Special Instrumentation:

As required for measurements of speeds, power requirements, fuel consumption, ride and handling characteristics, etc.

Environment:

Ambient atmospheric of selected test area(s).

9. FINAL TESTS OF LOCOMOTION SYSTEM (1/6 g Simulator) See Figure 8 of Text.

Purpose: To obtain final dynamic and steady state mobility per-

formance data for the Locomotion System under simulated lunar gravity conditions. Also to verify the validity of the analytical predictions of prototype performance, including predictions of the dynamic response and ride characteristics.

Test Articles:

Vehicle: Complete Locomotion System; full scale prototype mocked up to total MOLAB mass and cg configuration.

Special Test Equipment:

Lunar Gravity Simulation: Traveling, maneuverable overhead support system (See Figure 8); capable of maintaining constant lifting force of 5/6th Earth "g" on unsprung mass.

Traveling Camera Support Mechanism: Permits photographing of motion of vehicle relative to fixed horizontal plane; platform (multi camera mounting) moves at same horizontal velocity as vehicle but is not perturbed vertically; photographs vehicle against background reference grid(s).

Roadway: Large Roadway capable of adaptation to hard or soft surfaces; with or without obstacles; equipped with necessary mixing and homogenizing equipment.

Special Instrumentation:

As required for such measurements as power, internal wheel resistances, drawbar pull, external resistance, slippage and ride characteristics. Includes special cameras and other equipment for photographing vehicle motion.

Environment:

Ambient atmospheric. Humidity control desirable to maintain cohesionless soil.

APPENDIX C

LUNAR GRAVITY SIMULATORS
OF THE
INCLINE TYPE

LUNAR GRAVITY SIMULATORS OF THE INCLINE TYPE

When considering the use of inclines to simulate lunar gravity for various types of full scale, reduced gravity tests (e. g., astronaut performance and dynamic tests of lunar surface vehicles), several possibilities come to mind. Perhaps the two most promising types of such facilities are

1. An inclined plane set at 80.4 degrees to the horizontal with the astronaut or vehicle restrained in fixed position along an axis parallel to the plane by a cable system. This type of installation and its possible variations are well known (see Section 7.5 of text) and will not be discussed further in this appendix.
- and 2. A right circular cone frustrum which presents an endless runway for test usage. For the purpose of this analysis, only vehicle tests are considered. The vehicle is restrained against lateral motion, as in item 1, along an axis parallel to the slope of the roadway. When the roadway is equipped with obstacles and relative motion occurs between it and the vehicle, dynamic testing is possible. It should be noted that only hard surface tests would be possible on inclines, thus preventing the investigation of vehicle-soil interrelationships. In this analysis, two possibilities are considered.
 - a. The vehicle is oriented as shown in Figure C-1 and is driven around the cone at a constant tangential velocity. Except for the vehicle's interaction with the surface, the system acts as a conical pendulum.
 - b. Both the cone and vehicle are driven in such a manner that the peripheral velocity of the vehicle's wheels and the roadway are equal and opposite. Thus, the roadway becomes a treadmill and the vehicle can be operated at any desired speed without experiencing centrifugal force.

In the analysis which follows, these two cone frustrum type facilities are discussed separately.

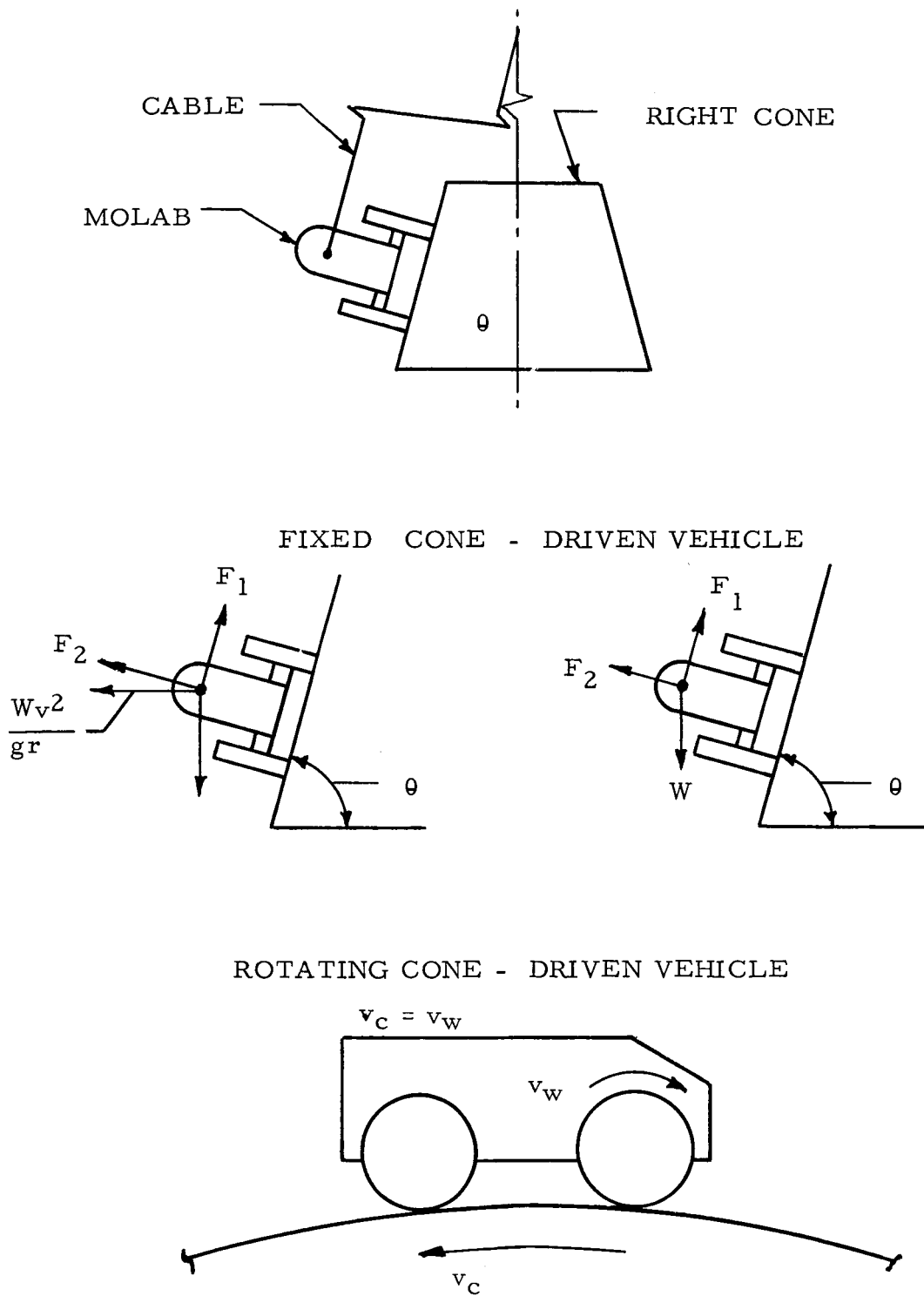


FIGURE C-1. LUNAR GRAVITY SIMULATOR - ENDLESS CONICAL RUNWAY

STATIONARY CONE-ROTATING VEHICLE

When the vehicle is driven about the surface of the cone, at a constant velocity, forces are generated as shown in the appropriate free-body diagram of the preceding sketch. Since the tangential velocity is constant, the following equations can be written:

$$F_1 \cos \theta - F_2 \sin \theta = \frac{Wv^2}{rg} \quad (1)$$

$$\text{and} \quad F_1 \sin \theta + F_2 \cos \theta = W \quad (2)$$

from which

$$F_1 = W \left(\sin \theta + \frac{v^2}{rg} \cos \theta \right) \quad (3)$$

$$\text{and} \quad F_2 = W \left(\cos \theta - \frac{v^2}{rg} \sin \theta \right) \quad (4)$$

Ideally, for true lunar gravity simulation, F_2 should equal $W/6$. For the plane surface, inclined at 80.4 degrees to the horizontal (case 1, above), this condition holds at any velocity, since centrifugal force does not enter into the physical relationships. Let us now consider the effect of centrifugal force on F_2 under the following assumptions:

$$v = 10 \text{ mph (14.67 fps)}$$

$$r = 100 \text{ ft.}$$

$$W = W$$

from equation (4)

$$F_2 = W (\cos \theta - .0671 \sin \theta)$$

$$\text{If} \quad F_2 = \frac{W}{6}, \text{ the value of the slope angle should be}$$

$$\theta \approx 76.6^\circ$$

If $\theta = 80.4^\circ$ (inclined plane value for lunar g simulation) the effect of a velocity of 10 mph is to decrease the runway reaction to

$$F_2 = .1014 W \simeq W/10$$

A more graphic picture of centrifugal effects can be obtained from an inspection of Figure C-2. This figure demonstrates the variation in the ratio ξ (roadway reaction/desired gravity reaction) with the radius of curvature of the vehicle path for various parametric values of velocity at the cone angle of 80.4 degrees. The following observations can be made for any steady state velocity:

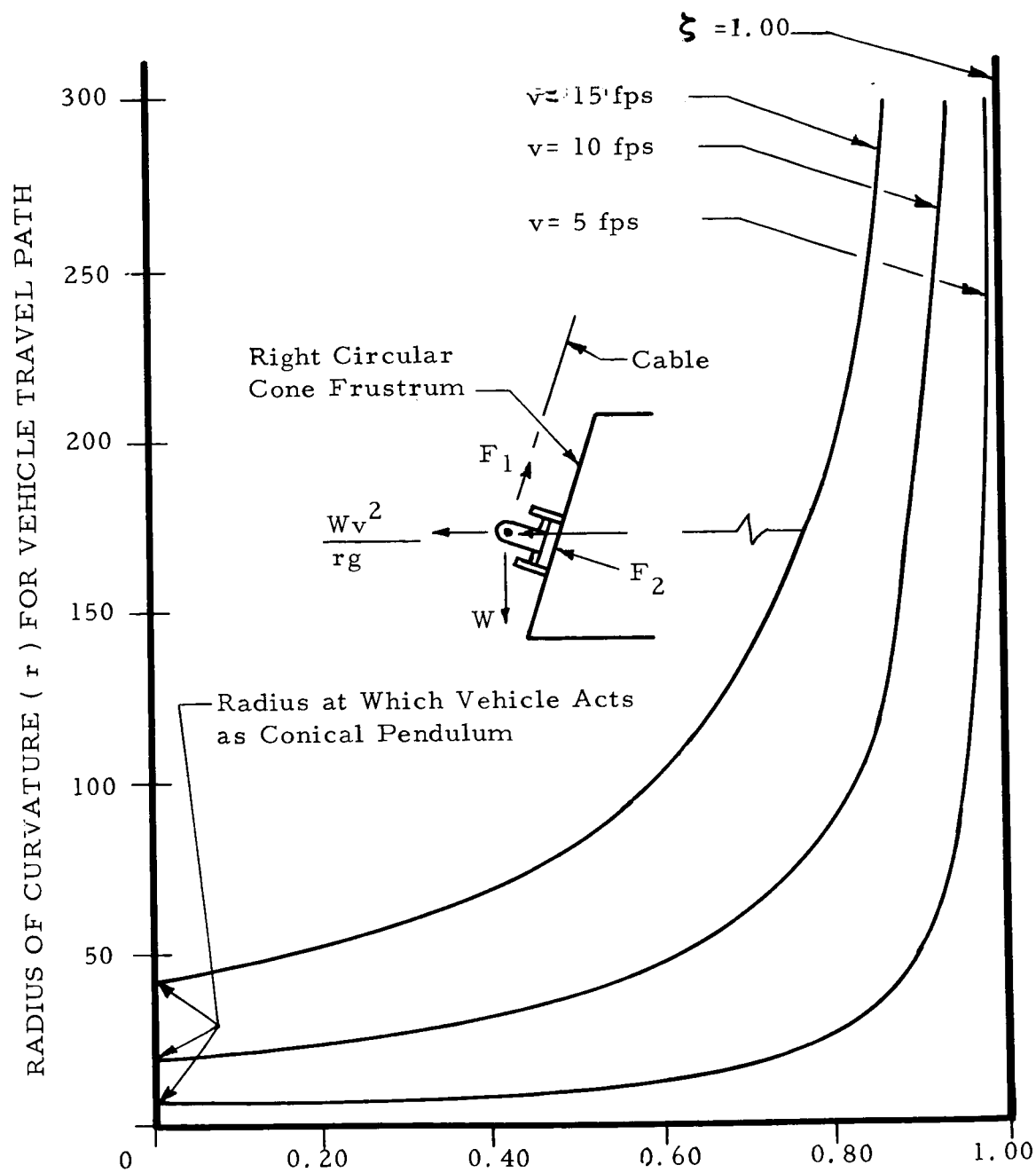
1. As the radius increases, the effect of centrifugal force decreases and the magnitude of ξ approaches that for a cone of infinite radius. For any chosen deg. slope, this is a ratio of 1.00. For 80.4 deg., the value of F_2 equals the force of lunar gravity and equates to the value for a straight slope at the same angle of inclination.
2. As the radius decreases, a limiting value is reached at which $\xi = 0$ (F_2 also equals zero) and the vehicle behaves as a true conical pendulum. At lesser values of radius, the vehicle will remain on the roadway only if a restraining force is applied. If this force is removed, it will leave the runway and seek this equilibrium radius as a conical pendulum.

Figure C-3 expresses the centrifugal accel. error in gravity simulation (Δg) in terms of earth gravity (g).

ROTATING CONE-DRIVEN VEHICLE

When the cone is rotated and the vehicle is driven at a velocity such that its motion relative to the ground is zero (see free-body diagram), centrifugal force is not involved. Consequently, if lunar gravity is to be simulated, the cone angle should correspond to that for the inclined straight plane, i. e., 80.4° .

A number of advantages are apparent in the use of this type of facility to investigate the dynamic response of the vehicle to vertical forces induced by obstacles, depressions and slope changes. For example, the fixed position of the vehicle relative to the ground permits the use of stationary background grids which, coupled with strategically placed cameras, can be used for studying the dynamic response of the vehicle to various types of obstacles. Photography is straight forward, since movies taken in real time would (when projected at real time) provide dynamic response data which closely simulates that which could



RATIO OF ROADWAY REACTION (F_2) TO IDEAL LUNAR GRAVITY ($W/6$)
 $\zeta = 6F_2/W$

FIGURE C-2. LUNAR GRAVITY SIMULATOR - CONE FRUSTRUM ROTATING VEHICLE-CENTRIFUGAL EFFECTS

LUNAR GRAVITY SIMULATOR
CONE FRUSTRUM-ROTATING VEHICLE
ERROR DUE TO CENTRIFUGAL FORCE

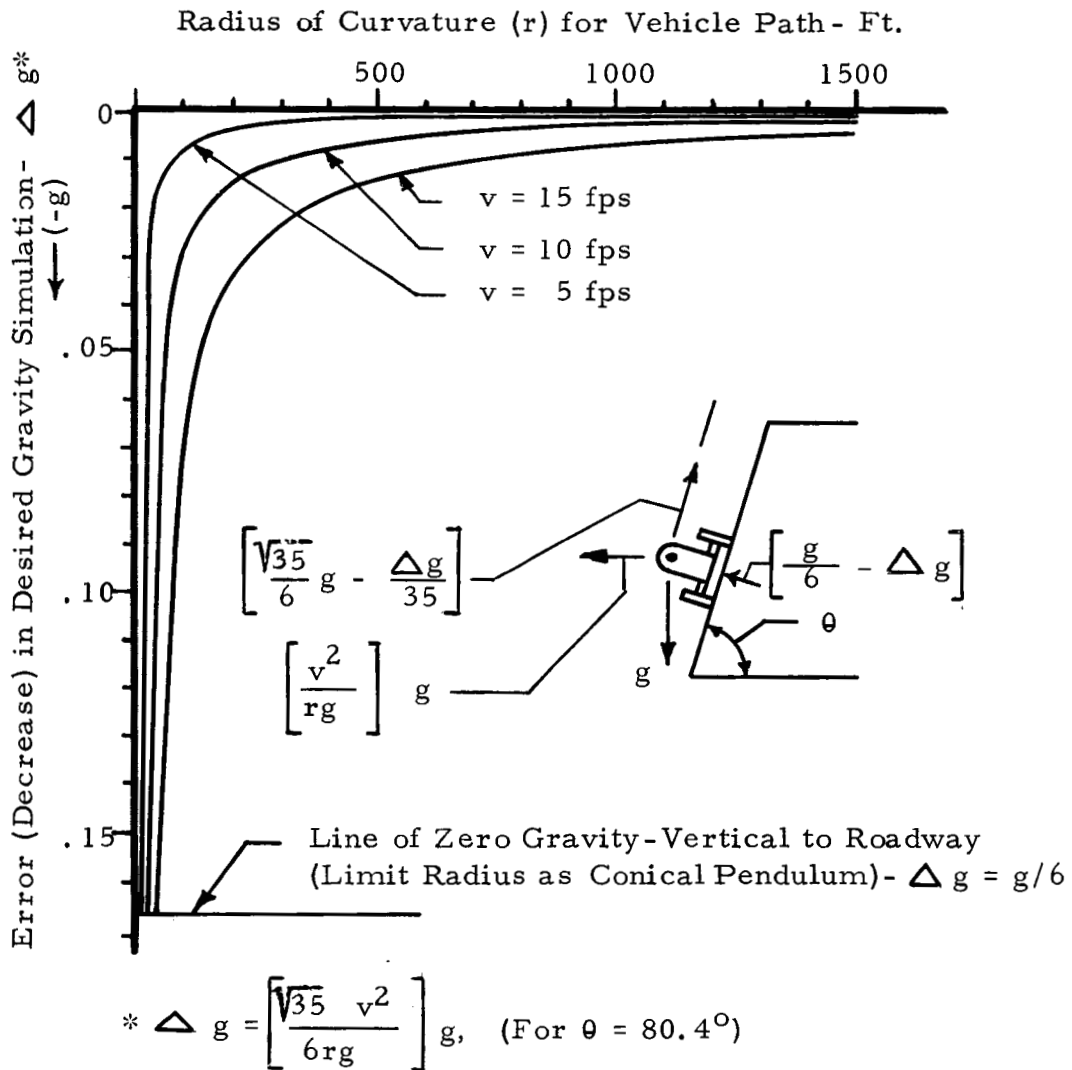


FIGURE C-3. LUNAR GRAVITY SIMULATOR - ERROR DUE TO
CENTRIFUGAL FORCE

be expected in the lunar environment. In addition, the end of the cable remains fixed and does not have to be synchronized with the forward travel of the vehicle, as in the case of the inclined (fixed) plane.

It should be noted that wheel side loads will be introduced by the cone because of the difference in travel between inboard and outboard wheels. Such loads would probably have a negligible effect on test results but, if proved to be troublesome, they could be minimized by the adoption of a sufficiently large cone radius. Also, the cable would have to be long enough that the change in gravity component vertical to the roadway would be small with respect to vertical displacement of the vehicle.

OTHER POSSIBLE APPLICATIONS

The test facility visualized in the preceding paragraphs is of a special purpose type; however, it may be feasible to expand its application to the determination of other aspects of vehicle performance, e.g., handling and stability characteristics. For this purpose, let us assume the necessary condition that the vehicle rotates about the fixed cone. If the height of the cone is sufficient to permit short duration upslope or downslope turns, a close approximation of lunar operations is obtained--provided the restraining cable maintains its tension force of F_1 --see eqn. (3). Two possible approaches to the solution of this problem are (1) moving the cone up or down (depending on the desired maneuver) along its vertical centerline in such a manner that the net effect on cable tension is negligible, and (2) the use of a load sensing device which provides the proper correction for maintaining constant tension as the vehicle is maneuvered up or down the cone.

The first of these approaches poses the problem of moving the cone vertically--no small problem. Its large mass would make this very difficult and necessitate provisions for a large amount of power. Other problems would be (1) synchronization of wheel steering with cone movement so as to simulate actual wheel side loads, and (2) changes in cable angle as relative motion occurs between the cone and vehicle. This latter condition would induce changes in the magnitude of the simulated gravity vector.

For the second approach, a reel could be used for the cable with a load sensing device connected to the reel through reduction gears. As the cable load varies during maneuvers, the sensing device would cause the reel to retract or extend the cable so as to maintain a constant

tension of F_1 - eqn. (3). The sensing device, for example, could utilize two oppositely rotating electric motors (one series wound and the other synchronous) connected to the cable reduction gear drive through a differential system. When operating at normal torque (equivalent to a cable tensile load of F_1), the series motor would turn at the same speed as the synchronous motor, thus maintaining zero rpm output through the differential. As the vehicle is maneuvered, the series motor would speed up or slow down (depending on the maneuver), causing the differential to rotate and extend or retract the cable in phase with the maneuver, thus maintaining the normal design torque and cable tension.

The latter of these two approaches appears to be reasonably feasible. However, positive determination of the feasibility of either is beyond the scope of this study. Further analysis, if considered desirable by MSFC, should treat the various problem areas in detail. In addition to those problem areas which are peculiar to the first approach (discussed above), the following are common to both approaches and are representative of those which should be investigated.

1. Simulation of lunar gravity for those components separated from the main body of the vehicle by the suspension system. Where suspension systems are used between the wheels and the upper part of the vehicle, separate restraint cables at the wheels would almost certainly be required when the vehicle rotates about the cone.
2. Centrifugal forces and their effect on the simulated gravity vector (see earlier discussion).
3. Methods of simulating lunar gravity conditions for the human operator of the vehicle. Note--techniques already in use at Langley, the Northrop Space Laboratories, and other test installations should be usable, provided certain modifications are made. For instance, if the vehicle is maneuvered relative to the cone, a means of maintaining constant cable tension would be required--see above discussion.

FINDINGS

In the foregoing pages, a preliminary analysis was made of several possible incline facilities of the right circular cone frustrum type which exhibit varying degrees of promise for use as lunar gravity simulators during tests of full scale vehicles. The scope of the analysis is

limited by its preliminary nature. However, pending further analysis, the following general conclusions appear to be substantiated:

1. The rotating cone (when used in conjunction with the driven vehicle as described in the analysis) provides excellent lunar gravity simulation and offers considerable promise for use in determining the vehicle's dynamic response to surface irregularities. It should also be noted that this type of facility appears to be superior to its progenitor--the inclined (fixed) plane--see previous discussion.
2. The fixed cone (rotating vehicle) installation has an objectionable feature, in that centrifugal forces affect the gravity simulation force. For example, at a cone angle of 80.4° and a vehicle path radius of 150 ft. (see Figure C-2), the magnitude of this force is 70% of the desired value at a velocity of 15 fps.
3. Use of the cone frustrum type facility for simulated maneuvers to obtain handling and stability data appears to be possible but, for such tests, the vehicle should rotate about the cone to properly simulate wheel side loads. Of the two approaches considered for producing relative motion between the vehicle and the cone for the simulation of turns--(1) movement of the cone along its vertical axis, and (2) movement of the vehicle over the surface of the cone--the latter appears to be reasonably promising.
4. A more detailed analysis of problem areas should be conducted to provide a basis for judgement relative to the advisability of using the cone frustrum type facility for other than the relatively straight forward dynamic response tests.

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